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Electricity & Magnetism

Theoretical & Practical

BY

C. E. ASHFORD, LL.D., M.A.

HEAD MASTER OF THE ROYAL NAVAL COLLEGE, DARTMOUTH
FOPMERLY SENIOR SCIENCE MASTER
IN HARROW SCHOOL

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PREFACE

THIS book is intended to provide in one volume theoretical and practical work in Electricity and Magnetism, from the stage of the beginner up to the standard required for University scholarships.

No attempt has been made to write up to (or down to) any syllabus; but judicious selection by the teacher, both of experiments and of what may be shown in the lecture-room, will provide material for most schemes of examination in elementary electricity. To facilitate this, paragraphs have been numbered, and some of the more difficult or less important have been printed in smaller type, or marked with an asterisk.

All three Parts are introduced by a series of experiments to be performed by the boy himself; it is intended primarily as a book to be used by him in a laboratory, although certain parts (e.g. Part II, Chaps. XI–XVI, where large currents and complicated apparatus are needed) are not well adapted to this treatment, and those parts are dealt with as lecture-notes.

The author's experience has convinced him that the knowledge gained by a boy from a course of lectures on the phenomena of current electricity is enormously greater if he has previously worked through a series of quantitative

experiments, such as is given in Chaps. I–VIII of Part II, and such experiments need no introduction viâ the lecture-room. The amount of reading in the laboratory between experiments, necessary to make them intelligible, is not excessive, and the power gained by a student of reading and acting on printed explanations and instructions is well worth the extra time spent as compared with that needed for merely repeating experiments he has seen in lecture.

To quote the Report of the Military Education Committee, in the more elementary parts of the subject 'the knowledge . . . should be such as could only be gained by working in a laboratory, the instruction given being in the main oral instruction in connection with the observations and experiments, formal lectures being made use of only to co-ordinate and consolidate the knowledge gained by laboratory work.'

A slight rearrangement of chapters in Part II will, however, provide a course such as is ordinarily given where the subject is taught chiefly in the lecture-room, most of the numbered experiments being then carried out by the lecturer and less prominence being given to the quantitative side of the subjects.

In a text-book necessarily containing, as well as directions for performing experiments, the statements of the deductions to be drawn from them, it is difficult to leave enough to the initiative of the student in the way of supplying explanations; but whenever it has been found possible the experiments are quantitative, and laws have to be actually discovered, not merely verified.

Attention has throughout been paid to the desirability of treating the subject inductively, not as a number of deductions to be verified by the student from a general law which he has no opportunity of proving. For example, lines of magnetic force are introduced by means of iron filings, not as a direct consequence of the Law of Inverse Squares.

Following the prevailing tendency, Magnetism has been treated in somewhat less detail than was formerly usual, rather as a necessary introduction to Voltaic Electricity than as a subject of value in itself. Educationally, Electrostatics covers the same ground and admits of more satisfactory experimental treatment.

The subject of Terrestrial Magnetism, in so far as it is not capable of investigation in a laboratory, has been treated very briefly, as being a branch of Navigation.

The book is so arranged that it is not *necessary* to read any Electrostatics before Voltaic Electricity. With the recent developments of the theory there is a tendency to restore to Electrostatics some of the importance it once possessed, but which it has lost of late years; nevertheless it is relegated to Part III because, without a fairly extensive experimental knowledge of the phenomena of current electricity, theory as to electrons in uniform motion cannot aid the student in realizing the laws of electro-magnetism.

There seems no valid reason for the common practice of defining the unit of current electro-magnetically, rather than by its legal electrolytic definition; in either case the measurement by a tangent galvanometer demands a certain amount

of preliminary mathematics, and it has a much simpler and more direct experimental basis in the case of the electrolytic definition. The orthodox method of dealing with the tangent galvanometer and current measurement gains a spurious simplicity from the temptation to the student (and not seldom even to the instructor) to slur over the difficulties by substituting unfounded assertions for reasoning. For example, he may be given the definition of unit current, and told that 'it will be found that the force between each element of current and a magnet-pole varies inversely as the square of the distance between them.' No suggestions are furnished as to how this may be proved experimentally; and a beginner does not always clearly grasp the idea of 'elements of current,' especially when they add their effects along a line at right angles to all of them. The result is a mental fog as to current measurement, from which he emerges only at the point where he meets the formula for the reduction factor; to that formula he learns to cling blindly. It seems to the author a matter of the greatest importance to impress on the learner at the outset the necessity of clear and honest thinking in science.

No apology is offered for the use of ammeters and voltmeters; their costliness has been hitherto (see p. 290) an excuse for their neglect in schools, which has led to a lamentable vagueness of thought and expression. Boys are not expected to weigh with arbitrary masses of their own manufacture, or to work with thermometers graduated on an arbitrary scale; it is difficult to understand why schoolmasters should still refuse to allow boys to measure

E.M.F. and currents in units intelligible to them. If, however, it is preferred, the use of ammeters and voltmeters can be entirely omitted without destroying the logical sequence.

The dissociation theories of electrolysis and solution pressure have been used to explain the action of the voltaic cell, polarization, electrolysis, &c.; they seem at least as easy of comprehension as Grotthüs' chain of molecules, and demand no more chemical knowledge.

Potential in Electrostatics has been frankly treated in two separate ways, the first introductory in Chap. IV, taking it on the analogy of temperature, the second in Chap. IX, based on mathematical reasoning from the mechanical definition. The introductory chapter is placed before that on Distribution of Electricity, but Chaps. V, VI, and VII can be read before Chap. IV if preferred. The analogies and differences between Potential and Temperature as set out in Chap. IV have been found to give to a boy, who has studied some Heat, a working idea of potential unattainable through the analogy of hydrostatic pressure, and certainly more exact and not further from the truth than the hazy notions usually acquired from an exclusive study of 'the work done on an imaginary charged particle.'

The elementary Theory of Electrostatics has been given with greater fulness than is common in elementary text-books, as even with very elementary mathematics results of great importance can be attained, and it forms a most valuable object-lesson in the application of mathematics to physics.

The diagrams, all of which have been photographed direct from amateur drawings, have been made as simple as possible, and in nearly all cases exactly as the student should draw them himself. Since the book is intended to supplement, not to replace, the use of apparatus by the student and the lecturer, ornate pictures of Leclanché cells, &c. are entirely superfluous, and merely add to the selling price of the text-book. The author gladly takes this opportunity of expressing his thanks to Professor J. J. Thomson, for permission to copy some diagrams of lines of force from his *Elements of Electricity and Magnetism*, and to his former colleagues at Harrow, Messrs. A. Vassall and J. Talbot, for their kindness in reading and criticizing the proof-sheets.

Summaries have been given only to the first chapters of Parts I and III, in order that the student may be left to summarize the others for himself.

The number of numerical exercises is not large, since a complete 'fair copy' of such exercises is sometimes created in a school, and passed on as an heirloom ; but typical examples are supplied in which the numbers can be varied.

The author will be very grateful for information as to errors, or suggestions for improvement.

August, 1903.

PREFACE TO REVISED EDITION

THE object of this revision is mainly to introduce some improvements in the methods of teaching; and in doing so, care has been taken to avoid inconvenience to those whose equipments and methods are suited to the former edition of the book, by introducing these changes as alternatives instead of replacements, and by preserving the original numbering of articles.

The use of commercial measuring instruments in place of tangent galvanometers needs no advocacy now; new articles have been introduced to provide a logical course which does not involve the magnetometer and tangent galvanometer.

The use of the Fluxmeter in lecture-room and laboratory is not yet sufficiently general to justify introducing it into the text; but an appendix has been added, in the hope that teachers will adopt this most direct and illuminating method of introducing beginners to the conception of the quantitative aspect of lines of magnetic force. One trial of the instrument will probably convert any one who doubts its value, which unfortunately is at present reflected in its cost.

The amount of space assigned to Part III is hardly justifiable, but is still required for schools in which the examinations for some University scholarships compel an emphasis on the mathematical side of physics. An outline

of a short course is given in an appendix, adapted to those students who need the ideas of charge, induction, &c., only so far as they enter into condensers, wireless telegraphy, and the problems of alternating currents; the treatment assumes some knowledge of current electricity, and is practical rather than theoretical, based on ordinary measuring instruments.

DARTMOUTH,
Jan. 1911.

PREFACE TO THIRD EDITION

THE time seems to have come when some at least of the results of recent researches, sometimes called the 'New Physics,' can safely be included in a text-book for beginners. A step in this direction has been taken by substituting for the chapter on Röntgen Rays, which appeared in former editions, an entirely fresh chapter. In it an attempt has been made to give in brief compass some of the broad generalizations from the discoveries of Sir J. J. Thomson and his school, and to illustrate them by the Thermionic Valve. Some other Articles (pp. 46, 169, and 201) have been rewritten, and an appendix on Ohm's Law substituted for an obsolete description of apparatus.

DARTMOUTH,
August 1920.

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ELECTRICITY AND MAGNETISM

PART I

MAGNETISM

CHAPTER I

Magnetic Attraction

1. A piece of steel can be permanently endowed with the property of attracting other pieces of steel or iron; it is then called a Magnet.

The magnet is most commonly made in the shape either of a straight bar or of a horseshoe, as in Fig. 1.

Fig. 1.

Experiment 1. Take a bar, or a horseshoe, magnet and some small pieces of iron such as 'tin-tacks,' or some iron filings, which are better because lighter. Test the power of attracting iron possessed by various parts of the magnet, and the distance from the magnet at which the force is perceptible; make a sketch of the magnet with as many iron filings as possible adhering to it.

Test the power of attraction for other substances, such as wood, paper, silver, steel (e.g. a sewing-needle), copper, &c. Procure small pieces of the metals nickel and cobalt, and find out if these are attracted, and if so, whether they are attracted as strongly as pieces of iron of the same size.

See whether this attraction for iron filings can be exerted through a sheet of paper, or of thin glass such as a microscope slide, of bronze such as a penny, of iron such as the lid of a tin.

The parts of the magnet which possess most strongly this power of attraction are called its **Poles**. The magnet is usually so made that the poles are at or near the ends of the bar.

EXPERIMENT 2. Take a bar-magnet about 15 cm. long; make a paper stirrup (*A*, Fig. 2) by doubling a piece of paper about 2 cm. wide and 5 cm. long, and hang it from a support (*B*) by a few fibres of unspun silk passed through holes in the two ends of the paper. The support (*B*) must be of such a kind that no iron is near the magnet.

Balance the bar-magnet in this stirrup and let it come to rest. Note the direction in which it points; disturb it from this position by bringing a bit of iron near one of its poles*, and note its behaviour when the iron is taken away. See if you can get the bar to settle down along the same line as before, but with its poles the opposite way round.

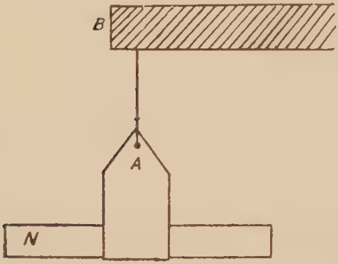


Fig. 2.

From a knowledge of the position (with respect to the laboratory) of the sun at its rising or setting you should be able to tell which end of the magnet points to the north. This is called the 'North-seeking,' or the 'North' pole, and is usually marked on the magnet by the letter N, or a line cut in the steel. If it is not so marked, attach a bit of gummed paper to this end.

Find out whether a horseshoe-magnet behaves in the same way when hung up.

2. Natural magnets have been known from very early times; the name comes from the Greek word μάγνης applied to an iron ore possessing the property of attracting iron, which was first found near Magnesia in Lydia. This iron ore is now called Magnetite (Fe_3O_4) and is used as a source of iron; only a small proportion is found to be naturally endowed with magnetic power, but any piece can be artificially 'magnetized.' The Greeks and Romans knew that these natural magnets were able to confer their own power on a piece of iron, if rubbed on it, without losing any themselves. Such discoveries were put to no practical use, however, until in about the twelfth century it was found that a long-shaped magnet when hung up turns round until it points about north and south. It is believed by some that this

* Note here as an illustration of Newton's Third Law of Motion, that the magnet is attracted by the iron as well as the iron by the magnet.

property was known to the Chinese as far back as 2000 B.C., but the whole of the early history of the subject is very obscure. From its use as a guide in navigation the stone obtained the name *Lodestone* (from an Anglo-Saxon word meaning 'course').

Dr. Gilbert, of Colchester, one of the physicians to Queen Elizabeth, who published the first serious book on magnetism in 1600, discovered that the reason why lodestones and magnets try to turn so that they point to the north is that the earth is itself a great magnet, with poles near the geographical north and south poles. He constructed a model of the earth from a piece of lodestone that produced the same effects on small compass-needles on its surface.

3. Experiment 3. **Action between two poles.** Take another bar-magnet and by suspending it as in Experiment 2 determine and mark its N. pole.

When this second suspended magnet has come to rest bring up towards its N. pole, from E. or W. of it, the S. pole of the first magnet (i.e. the pole which pointed to the south), holding it so that its N. pole is as far away as possible from the suspended magnet. Note whether it attracts the second magnet.

Repeat the experiment, presenting now the N. pole of the first to the N. pole of the second, and note whether they attract one another.

Repeat the experiment, bringing the two poles of the first magnet in succession near to the S. pole of the second.

You learn from Experiment 3 that the two poles of a magnet have opposite properties, although they are alike in their power of attracting iron; also that *two like poles repel each other, two unlike poles attract each other.* This may be considered the First Law of Magnetism.

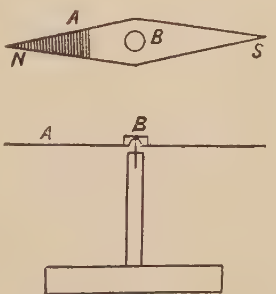


Fig. 3.

4. Compass-needle. The method of suspension by means of a stirrup is not convenient, and it will be better to use a 'magnetic needle' of the kind employed in pocket-compasses. This consists of a flat lozenge-shaped piece of steel, as (*A*) Fig. 3, which has been magnetized; in the centre of this is fixed a cap (*B*) of brass, glass, or agate mounted in brass, made cup-shaped so that it can be supported on a point. The point is usually a steel needle fixed in a brass stand,

such as a drawing-pin upside down. One end of the compass-needle is usually 'blued' to indicate that it is the N. pole.

With this we can test whether a substance is magnetic, i. e. whether it is capable of attracting and being attracted by a magnet, or whether a body is itself a magnet. The student must bear in mind that attraction alone does not prove the latter, for the thing attracted may be itself a magnet; if the extremities of the body to be tested are slowly brought near each pole of a compass-needle in succession and fail to repel either of them at any point, then it is not a magnet *; if it attracts them it is a magnetic substance.

EXPERIMENT 4. **To magnetize a needle.** Take a sewing-needle, lay it on the table and hold it firmly by one end (note which end). With one pole, say the N., of a bar- or horseshoe-magnet stroke the needle from the point where it is held to the opposite end. Bring the stroking pole back to its starting-point, carrying it well away from the needle, and repeat the stroking four or five times. Now with the help of the compass-needle test the position and kind of poles that have been produced in the needle, especially noting whether you find the same (or opposite) pole as that of the stroking magnet at the end of the needle last touched by the magnet.

This is the most primitive method of magnetizing a bar, and is known as the method of **Single Touch**. Better methods will be described later (pp. 12, 131).

EXPERIMENT 5. **Action of the earth only directive.** Take a sewing-needle, magnetized as in Experiment 4 (determine whether the eye or the point should be N.), and, by means of a fork made by bending up a piece of copper wire, lay it carefully on the surface of still water in a large beaker. The needle will float if this is done very gently, and care is taken that it is exactly horizontal when it touches the water; then if the needle is so far from the side that the surface tension, or 'capillarity,' does not cause it to move, you can determine whether the attraction of the earth, which makes the needle set north-and-south, also causes the needle to move bodily in either direction. If not, it must be that the attractions on the two poles of the needle are equal and oppositely directed along the same straight line, which is the line along which the needle lies.

EXPERIMENT 6. **Consequent poles.** Although hitherto we have

* This test is not altogether exhaustive; consider for example the case of a ring magnetized along its length.

only considered cases in which the poles are situated at the ends of a bar, it is easy to produce them elsewhere. For example, take a knitting-needle (*A B C D*, Fig. 4).

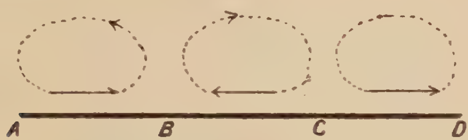


Fig. 4.

With a magnet-pole (say N.) stroke from *A* to *B*, from *C* to *B*, and from *C* to *D* as in Experiment 4. By bringing it near the compass-needle determine the position and kind of the poles produced, and mark them in a diagram.

EXPERIMENT 7. **Destruction of magnetization.** By the method of single touch magnetize as strongly as you can a piece of flat clock-spring about 10 cm. long. Observe the amount of the power of one of its poles to repel the like pole of the compass-needle when held a short distance away, say about 2 cm. Now throw the newly made magnet several times on the table, bend it about and otherwise subject it to rough treatment. Observe the effect it now has on the compass-needle when held at the same distance as before. Has the magnetization been diminished?

Re-magnetize the clock-spring strongly, and then heat it red hot in the flame of a Bunsen burner; when it is cool again test the magnetization.

This experiment shows that the 'permanent' magnets which you use demand careful handling if their strength is to be maintained.

Now magnetize as strongly as you can a strip of iron of the same size as the piece of clock-spring (a piece of tinned iron, or 'tin' cut from a biscuit tin does very well); compare its power of retaining magnetization with that possessed by the steel.

Steel is said to have considerable *Retentivity*, and soft iron (i.e. iron which possesses little elasticity and can be filed easily) has very little.

5. Iron and steel. Steel and iron differ chiefly by the amounts of carbon which they contain. Cast iron contains 3 or 4 per cent., steel usually about ·7 per cent., and wrought iron less than ·15 per cent. of carbon. There are also differences in the condition of this carbon in different cases; sometimes it is chemically combined with the iron, sometimes distributed in microscopic crystals throughout it. Steel

can be *hardened* and *tempered*. These properties are not shared by iron. If a piece of steel is heated to redness and suddenly plunged in water or oil, it becomes 'glass-hard' (i. e. will scratch glass) and very brittle. If it is now again heated to redness and allowed to cool slowly, it loses these properties and becomes comparatively 'soft,' and can be bent far beyond its limits of elasticity without snapping. If after it has been made glass-hard it is heated to a temperature below redness and allowed to cool, it assumes a state intermediate between glass-hard and soft; this is called *tempering* the steel. If when the steel is glass-hard the surface is cleaned with emery cloth, and the heating is then carried on slowly in a good light, as the temperature rises colours will be seen to spread over the surface (due to thin films of oxide) in the following order—light straw, dark straw, brown, violet, blue. These surface colours, which are permanent, show the degree to which the steel has been tempered; if the process is stopped at the straw-coloured stage the steel will be very hard and will have a very high retentivity for such magnetization as it can be induced to assume. The steel for magnets is usually of a blue temper; it then has a fair retentivity and can be easily magnetized by another permanent magnet.

The addition of other substances besides carbon affects the magnetic properties of iron; thus a small percentage of Tungsten greatly increases the retentivity, and is usually added to steel for permanent magnets; while the addition of 12 per cent. of Manganese produces a steel which it is impossible to magnetize.

6. It may be mentioned here that the magnetization produced in a piece of hard steel by any of the ordinary processes is little more than skin deep, and so disappears almost entirely if the surface layer is dissolved away by sulphuric acid. This effect is more marked when the steel is hard, so that the interior of a permanent magnet is of little value; the difficulty can, however, be overcome by building it up of a number of thin sheets of steel separately magnetized and then bolted together, forming what is called a compound, or **laminated**, magnet. This is not necessary in the case of a magnet made of soft iron, kept magnetized by an electric current (see p. 131).

Summary of Chapter I.

A magnet attracts pieces of iron, nickel, and cobalt, but not of other substances; the force is perceptible only at a short distance from the magnet.

Some parts of the magnet, called its Poles, attract more strongly than others.

Pieces of magnetite are found which are natural magnets.

An elongated magnet, when hung up so as to turn freely in a horizontal plane, turns until it points N. and S.

Like poles repel each other; unlike poles attract each other.

A body is not a magnet unless some part of it repels one pole of a compass-needle.

A bar of steel can be magnetized by stroking it from one end to the other with one pole of a magnet.

A magnet when perfectly free to move horizontally does not move bodily either to the N. or the S.

Magnetic poles can be produced in the middle of a bar of steel.

Rough treatment or high temperature lessens the strength of a magnet.

Steel possesses high retentivity, especially if hardened, while soft iron possesses practically none.

The magnetization of hard steel is only skin-deep.

CHAPTER II

Magnetic Induction

7. Experiment 8. Take a bar of soft iron, such as a French nail or the strip of 'tin' used in Experiment 7, and by means of a compass-needle see whether it is magnetized; if so, knock it about until it is not.

Hold it upright with its lower end in a heap of iron filings, and bring near to its upper end one of the poles of a bar-magnet, as in Fig. 5. Observe whether the soft iron now attracts the filings, lifting it out of the heap to see if it carries them with it. Take away the magnet and observe any change in the attraction.

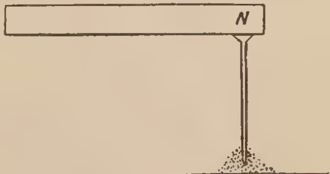


Fig. 5.

A magnet-pole is said to **induce** magnetism into any iron placed near it. The last experiment shows that it induces a pole in the extremity of the iron furthest from the

inducing pole; we must now see if other poles are induced, and whether they are N. or S.

EXPERIMENT 9. Lay a bar-magnet on the table, and at a short distance from it lay a piece of soft iron in the same direction, as *A B* in Fig. 6.

Sprinkle iron filings on the soft iron and observe where they gather on it in tufts as they did on the poles of the magnet in Experiment 1. Sketch the result, and mark on your sketch the position of any poles you discover.

Fig. 6.

Next support the magnet (*S N*, Fig. 7) and soft iron bar (*A B*) on a wooden block, and bring the end of the iron bar, which is most distant from the magnet, towards one pole of a compass-needle (*C*). Remembering that like poles repel, unlike poles attract each other,

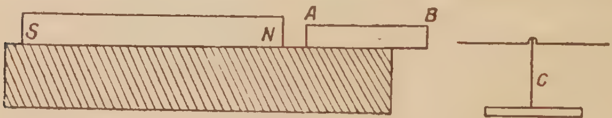


Fig. 7.

and that the North pole of *C* points to the north when unaffected by neighbouring iron, determine whether *B* is a North or South pole, first when the North pole of *S N* is nearest to *A*, then when the magnet *S N* is turned end for end. In Fig. 6 mark the end *B* with N. or S. in accordance with what you find.

If you can get a really small pocket-compass, such as will be used in Experiment 16, put it in the position of the letter *A* in Fig. 6, and so determine the kind of pole you get at *A*, and mark the end *A* with N. or S. accordingly.

We learn from this that *when a piece of iron is magnetized by induction, the end nearer to the inducing pole acquires opposite 'polarity,' while the further end acquires polarity similar to that of the inducing pole.*

We are at liberty to assume that when a magnet-pole attracts a piece of unmagnetized iron or steel, it does so in virtue of the fact that it first induces an unlike pole in the part of the iron nearest to it, which it then attracts according to what we have called the First Law of Magnetism.

Suppose now that a strong magnet-pole is put near to the similar pole of a compass-needle, which is held in position so that the normal repulsion between them cannot cause it to move away. The magnet-pole will induce an opposite pole in the nearer end of the compass-needle, and so weaken its former pole-strength ; if the magnet-pole is strong enough compared to that of the compass-needle, the polarity of the latter will be reversed and attraction will occur. The same thing will happen to the magnet-pole if that is weak compared to the needle ; hence if we have to test whether a pole is N. or S. we must bring it up towards a compass-needle *slowly*, looking out for the first signs of repulsion. The student can easily make the end of a magnet and of a compass-needle, which formerly carried like poles, attract one another by bringing the magnet-pole very rapidly close up to the compass. He should notice whether this permanently reverses the polarity of the compass-needle.

EXPERIMENT 10. Support a bar-magnet vertically by a clamp (*B*, Fig. 8), and hang from its pole a short soft iron nail, say 2 cm. long ; see whether you can suspend a chain of them as in Fig. 8. If so, each induced magnet must be capable of inducing magnetism in the next.

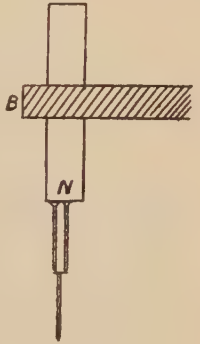


Fig. 8.

Hang two or three sewing-needles or pieces of thin soft iron wire, instead of the nails in Fig. 8, *side by side* from the pole of the magnet, so that each is touching the magnet ; observe whether their lower ends hang towards or from one another, and explain the reason of what you observe. (Remember that unlike poles attract, like poles repel each other.)

Suspend as long a chain of nails as you possibly can, as in Fig. 8 ; suppose that the pole supporting the chain is a N. pole, bring up the S. pole of another magnet to the middle of the supporting magnet and slide it down until it reaches the supporting pole. Observe and account for the result. Repeat this, using the N. pole of the second magnet ; again account for what you observe.

Now bring up the N. pole of the second magnet below the bottom end of the longest chain of nails which the supporting (N.) pole will hold ; note and account for what happens.

Experiment 11. **Comparison of iron and steel under induction.** It was seen in Experiment 7 that steel has considerable retentivity for magnetism, soft iron very little; you should now compare the magnetic strength of iron under induction with that acquired by steel in the same circumstances. In order that the comparison may be fair, you must take pieces of hard steel and soft iron of the same size and shape. A French nail about 4 cm. long and 2 mm. thick, and a piece of the same length broken from a steel knitting-needle of the same thickness will serve very well. Hang these, one from each pole of a horseshoe-magnet, and dip their lower ends into a heap of iron filings; compare the amounts they pick up. Remove them from the poles, and see what parts are permanently magnetized most strongly, and compare the retentivities of steel and iron.

Now make the steel glass-hard (p. 6) and repeat the experiment; does glass-hard steel or steel of an ordinary temper take up magnetism the more easily?

The results of this experiment and that of Experiment 7 may be expressed by the statement that hard steel possesses less **susceptibility** but more retentivity than soft iron; i. e. it is less easy to magnetize, but retains a larger proportion of what magnetism it takes up, when the magnetizing force is removed.

8. In no instance hitherto has a magnet been used or made that possesses only one pole; the obvious way to make one is to break a bar-magnet in the middle.

Experiment 12. **Result of breaking a magnet in two.** Harden a knitting-needle or a piece of clock-spring about 10 cm. long, as described on p. 6; magnetize it by the method of single touch so that it has a pole at each end. By means of iron filings or a compass-needle determine the point of the steel where there is no magnetic attraction, and break it at that point. If you use a knitting-needle, you must hold it in a pair of pliers near that point and try to bend it there.

Test the broken pieces with iron filings and with a compass-needle to discover where the poles are situated and whether these poles are N. or S. poles. Mark them in a diagram like Fig. 9.

Fig. 9.

Break each half again and again until the pieces are too small to

break, and see whether you can obtain a piece of steel having only one pole.

It is thus seen that every piece of magnetized steel possesses at least two poles.

9. Theory as to the molecular condition of a magnet. Since every piece of steel formed by breaking a magnet possesses a N. and S. pole, it is reasonable to suppose that, if this process was continued until each piece consisted of a single molecule, each would have a N. and S. pole, pointing the same way as in the original bar. We can then imagine a magnet as consisting of an enormous number of molecules, each of which is a tiny magnet, arranged in lines with the same pole of each in the same direction, as in Fig. 10. Until the molecules are separated by breaking the bar, the N. pole of one neutralizes the S. pole of the next, except at the ends of the bar.

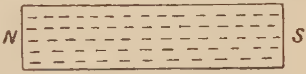


Fig. 10.

This would produce a bar having poles only at the ends, which we have seen does not occur in practice; a more probable arrangement of the molecules is shown in Fig. 11.

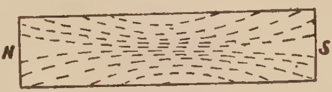


Fig. 11.

The question remains, are the molecules made into magnets when the bar is magnetized, or are they always magnets which are, so to speak, only 'combed out' into lines on magnetizing the body? We cannot answer this question with certainty, but many different experiments suggest that the latter hypothesis is the true one; that in an unmagnetized piece of magnetic material the molecules are all tiny magnets arranged 'at random,' as in Fig. 12, and that the more strongly the material is magnetized, the greater is the number of these tiny magnets that fall into line. This theory accounts for the observed fact that there is a limit to the amount of magnetism that can be induced into a bar, however great the magnetizing force; the material is then said to be *saturated*, which would occur when all the molecules were aligned.


Fig. 12.

10*. Cause of magnetism of the atom of iron. If an electric current flows round a circular ring of wire, it produces magnetic effects at points

near the wire, as though a short magnet was placed at the centre of the ring (see p. 131). Now the modern theory as to electric currents is that they consist of streams of *electrons*, or fragmentary electric charges, moving in the direction of the current (see pp. 169, 201).

It is also supposed that every atom of every substance contains at least one negative electron, whose charge is neutralized by the existence in the atom of an equal positive charge (see p. 201).

These electrons have a size almost negligibly small compared even with an atom, being of about one seven-hundredth of the mass of a hydrogen atom, and perhaps one ten-millionth the size.

Hence it is quite possible that the magnetism of the atom is caused by a rapid revolution in a circular path of such an electron round it (as the earth revolves round the sun). By this means the same effect would be produced outside the atom as if the atom were a 'magnet.'

11. This idea of the rearrangement of molecules can be realized on a large scale by the following experiment:—

EXPERIMENT 13. **Behaviour of a tube of steel filings under induction.** Take a long thin test-tube, and put steel filings into it until it is two-thirds full; iron filings will do if no steel filings are available. Cork it up and test whether it is magnetized or only a magnetic material. Carefully magnetize it by single touch, or better, by passing an electric current round it as described on p. 131. Carry it with care to a compass-needle and determine whether it now possesses poles; examine the filings to see whether they are arranged in lines. Try whether vibration while under induction increases the magnetization. Next shake the tube vigorously when not under induction and see whether the magnetization is destroyed.

These theoretical considerations will make clear the advantages of the following method for magnetizing a straight bar. Suppose *A B* in Fig. 13 is the bar to be magnetized, and that a S. pole is required at *A*. Lay *A* on the N. pole of a strong magnet, *B* on the S. pole of another strong magnet; take

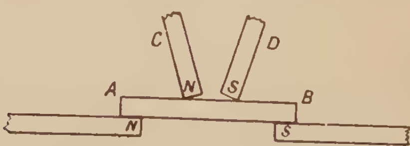


Fig. 13.

two bar-magnets *C* and *D* and put the N. pole of *C* and the S. of *D* together at the centre of *A B*, and simultaneously draw them along to *A* and *B* respectively. Repeat this many times, and *A B* will be magnetized fairly uniformly and strongly.

12*. Grouping of Molecules. It has been shown by Professor Ewing that the small susceptibility of hard steel is probably due to the mutual attractions of the poles of the molecules, which hold the molecules *in groups* (instead of their being distributed at random as in Fig. 12) until disturbed by the greater strength of the outside magnetizing force. If this force is small it merely alters slightly the directions of the little magnets, producing in the aggregate a small magnetization of the body. If it increases, it disturbs the grouping and the molecules swing round, and the group then contributes largely to the magnetism of the bar. This breaking up of a group is followed by a violent swinging to and fro of the molecules about their new positions; this will, of course, imply a change of energy into the form of heat, which is observed if the magnetism of a piece of iron is frequently and rapidly reversed. This theory satisfactorily accounts for all the phenomena of Hysteresis, &c. (see p. 140).

13. Keepers for permanent magnets. In order to retain in permanent magnets as much magnetism as possible, they should always be provided, when not in use, with 'keepers,' consisting of bars of soft iron connecting their poles, as the shaded parts in Fig. 14. In the case of a horseshoe-magnet the keeper is made to join the two poles; bar-magnets are often kept in pairs in a box with their like poles at opposite ends and a piece of soft iron to join them, or they may be kept in pairs touching one another with unlike poles together.

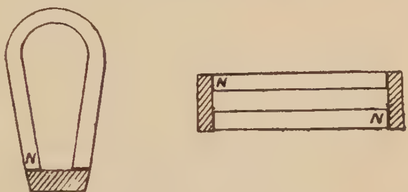


Fig. 14.

The advantage of this should be clear from what has been said of the molecular condition of magnetized steel and the induction of magnetism in soft iron. In a magnet without a keeper the chains of molecules tend to break up into groups, but when the keeper is put on, magnetism is induced in the keeper, i. e. its molecules are arranged into chains continuous with those in the magnet, and so closed rings are formed in which every molecule has each of its poles held by the unlike pole of the next molecule of the chain, so that even under vibration there is much less tendency to break up into groups.

14. Tendency of a short magnet to demagnetize itself. If we consider the inductive effect of the poles at the end of a magnet on the steel of the magnet itself, we see that these poles tend to reverse

the polarity of the magnet; in the language of our theory as to the molecular condition of a magnet, the repulsion of the N. pole of the magnet on each of the N. poles of the tiny molecular magnets tends to make them face round towards the S. pole of the magnet; the result of this would of course be to destroy the magnetism. It is only because the force used to magnetize the bar is stronger than this demagnetizing force that any magnetism is produced; and there should now be no difficulty in accounting for the feeble magnetization noticed in the actual ends of the bar, where this demagnetizing force is strongest owing to the proximity to the poles.

The poles on the ends of the bar have much greater effect in demagnetizing a short than a long magnet; and the advantage of a keeper can be explained by the fact that it practically eliminates these poles.

CHAPTER III

Lines of Magnetic Force

15. At any point of the space surrounding a magnet, a piece of iron or the pole of another magnet experiences a force. This space is consequently called a Field of Magnetic Force, though it must be clearly understood that magnetic force, like any other force*, can only exist where there is matter, since 'Force is that which changes or tends to change the motion of Matter.'

Unless it is expressly stated to the contrary, the force at any point of a field of force will imply the force exerted on a *North pole*, not the total force on a *particle* of iron, situated at that point.

In practice it is, as we have seen, impossible to obtain an isolated north pole, but we can get over the difficulty by magnetizing a very long thin steel wire and using its end as the pole; for the south pole will be far away and unaffected by the force at the point in question.

The following experiment will give an idea of what is meant by this:—

Experiment 14. **Force at a point of a magnetic field.** Lay a bar- or horseshoe-magnet on a piece of paper; magnetize, as strongly as possible, a darning-needle about 6 cm. long, to have a N.

* The student will later come across the ideas of 'electromotive force' and 'magnetomotive force,' but no confusion should be caused, because their names show that they are not true forces, but only tend to move electricity and magnetism respectively, not the bodies carrying the electricity or the magnetism.

pole at the point and a S. pole at the eye; suspend it, by a silk fibre about 10 cm. long passed through its eye, so that its point almost touches the paper at various positions in the neighbourhood of the magnet. The magnetic force on the pole at the needle-point will deflect the needle from the vertical in the direction of that force, so that you can draw a line from any point roughly in the direction of the magnetic force there, as in Fig. 15, where NS is the magnet, AB the needle. In this way the whole paper could be marked with arrows showing the direction of the force at any point of it; but it would be a tedious operation.

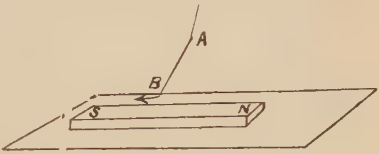


Fig. 15.

Sprinkle fine iron filings thinly and evenly over the whole paper, by holding a piece of wire-gauze about 20 cm. above it, shaking the wire-gauze about while you slowly pour the iron filings on it. Tap the paper gently, and the filings will arrange themselves in lines which begin and end on the magnet, as roughly depicted in Fig. 16.

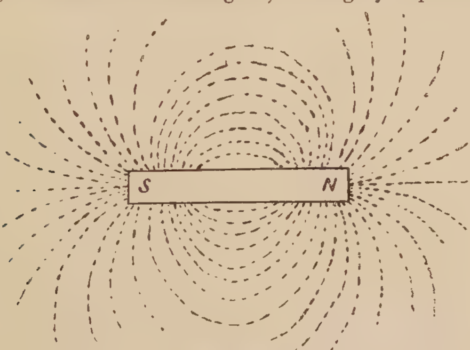


Fig. 16.

By means of the suspended darning-needle, see what relation the direction of the magnetic force at any point of one of these lines bears to the direction of the line itself at that point. You will probably conclude that it is the same; that is, that these lines of iron filings mark the lines along which the magnet urges a N. pole.

Faraday (Professor of Physics at the Royal Institution from 1833

to 1867), who first investigated their properties, called these lines the **Lines of Force** of the field; the existence of such 'magnetic figures' was known to Lucretius. They clearly map out the space in the immediate neighbourhood of magnets, and as will be seen later (p. 272) they can be used to indicate not only the direction of the magnetic force at any point of the field, but also its intensity, i. e. the magnitude of the force on a pole placed at that point.

The figures may be made permanent by many processes, the simplest being to use a piece of ordinary smooth 'printing-out' photographic paper on which to sprinkle the filings; the whole can be left in daylight until the parts of the paper not covered by the filings have darkened, and then fixed by immersion in a bath of sodium hyposulphite.

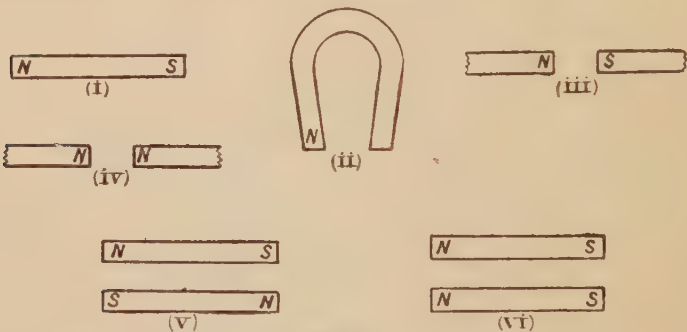


Fig. 17.

EXPERIMENT 15. **To discover the lines of force near various combinations of magnet-poles.** Obtain the magnetic figures near the following arrangements (i–vi, Fig. 17) of magnets, and make a sketch of each in your note-book, as in Fig. 16. It is better to put the paper *above* the magnets, better still to use thin 'Bristol board' instead of paper, as it is stiffer.

Also fix a bar-magnet vertically and support the paper or card-board over its upper pole; find the lines of force on the cardboard.

16. By studying the arrangements of the lines of force, it will be seen that they always start out from a N. pole *, and that they run to

* Remember that a line of force has 'sense' as well as 'direction,' i. e. that there is a *positive* and *negative* direction. The positive direction is that in which a N. pole would be urged, while a S. pole would tend to travel in the negative direction.

a S. pole when possible, not in straight lines but rather as though they repelled one another and sought the least crowded path from pole to pole. Incidentally it may be noted that they can never cross one another; naturally there cannot be two directions at any point of space, along which a N. pole placed at that point would be urged to move; if two forces act simultaneously on a pole the direction in which the pole moves is that of their 'resultant,' a direction lying between the lines of action of the two forces.

It is not difficult to see why the filings arrange themselves in chains in this manner along lines of force; each filing is an irregular body which is, naturally, longer in some one direction than in any other, and probably contains some permanent magnetism. It can be proved that in such elongated bodies the magnetic poles tend to locate themselves at the ends, so that each filing is like a little compass-needle. When the paper is tapped the filings are left for a moment in the air, so that they turn with their N. poles pointing one way and their S. poles the other along the line of force passing through them, and so join on to the next filings on that line of force to form a chain.

This process of mapping out the lines of force is only applicable where the magnetic force is strong. At other points of the field of force they can be traced by the help of a delicate little compass-needle made for the purpose, in which the needle is not more than 1 cm. long enclosed in a small brass case. As there is much less friction than in the case of filings on paper, the needle sets along the line of force even when the force at the point is very weak. Thus the direction of the force can be found at points distant from the magnet. In order to trace out a line of force the method of Experiment 16 should be adopted.

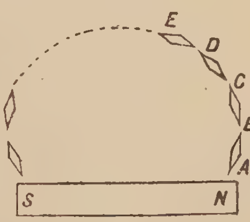


Fig. 18.

Experiment 16. **To map a field of force by an exploring compass.** Fix a large piece of paper on the table, remove all magnets from the table, and by means of a compass determine the north-and-south line through the middle of the paper. Lay a bar-magnet (about 12 cm. long) along this line with its N. pole pointing south (Fig. 18). Draw a line round the magnet, so that it may be exactly replaced if it gets moved. Lay a small exploring compass on the paper near the N. pole of the magnet, and when the needle has come to

rest, mark dots (A and B) with a pencil as near its two ends as you can get. The line $A B$ is approximately a fragment of a line of force. Move the compass until the S. pole is close to B (where the N. pole was); put a dot (C) at the new position of the N. pole of the needle, and so on. The compass will thus be gradually moved so that its centre traces out a line of force, which can be obtained on the paper by drawing a smooth curve through the points A, B, C, D, &c.

Draw lines in this manner, starting from fresh points, until the whole of the paper has been mapped out by lines not very distant from one another. Mark an arrow-head on each to indicate the direction in which a N. pole is urged. Make a reduced sketch of the result in your note-book.

17. An examination of the map of the field of force obtained in Experiment 16 will show that near the magnet the lines run as shown in Fig. 16, but that at more distant points they seem to follow a different law. For example, at two points (P, P', Fig. 19) in the line of the magnet they are grouped, as shown, round a point through which no line of force seems to pass. The student probably found a good deal of difficulty in tracing the lines in the neighbourhood of these points, as the forces there are weak and the lines of force are sharply curved. At the actual points P and P' the needle, if very short, will rest in any position, showing entire absence of force.

Fig. 19.

The explanation is that the force of attraction of the earth exactly neutralizes that produced by the magnet; the S. pole of the latter pulls a N. pole at P towards it with slightly greater force than the repulsion of the N. pole of the magnet, since it is the nearer pole and it was seen (Experiment 1) that the force decreases as the distance from the pole increases; and the difference between them is exactly equal to the attraction northwards exerted by the earth. This attraction of the earth is constant in magnitude and direction at all points of the paper.

It will also be noticeable that the field of force of the magnet is, so to speak, self-contained; all lines of force leaving the magnet return to the magnet, while those towards the edges of the paper run from the S. to the N. pole of the earth, but are distorted from their usual parallelism by the presence of the magnet.

These maps take a long time to make, but they are extremely

instructive and the information given as to the behaviour of lines of force is invaluable, since for practical purposes a magnet's sole use is to be the starting point of a number of lines of force; these lines must be thought of as moving about with the magnet, and disturbing other fields of force when the magnet is introduced into them.

EXPERIMENT 17. **Map of resultant fields of force of the earth and a bar-magnet.** Lay your bar-magnet along a north-and-south line as in Experiment 16, but now turn the N. pole of the magnet towards the N. Prepare a map of the 'resultant' field in the same way, and a reduced sketch in your note-book.

EXPERIMENT 18. **Field near a magnet placed east and west.** Lay your bar-magnet at right angles to the north-and-south line, i. e. east-and-west, and prepare a map of the field round it as before, and a reduced sketch.

These two experiments will show that lines of force coming from the earth's 'south pole' may be deflected from their course and pass into the magnet at its S. pole, reappearing at its N. pole and proceeding to the 'North pole' of the earth. Now a previous study of the lines of force showed that they always started at a north pole and ran to a south pole, so that we must assume that the 'south pole' of the earth is really a north pole, as we have defined a N. pole; a fact that is otherwise obvious, since it attracts the south pole of a freely suspended compass-needle.

18. Soft iron in a field of force. The introduction of a piece of soft iron into a magnetic field of force will alter the distribution of the lines of force, though the disturbance is quite different from that produced by the introduction of a magnet with its own lines of force.

EXPERIMENT 19. Take two bar-magnets, and lay them down in the position of Fig. 17 (iii), leaving between their ends a space long enough to take a soft iron keeper with a gap of about 1 cm. at each end, as in Fig. 20.

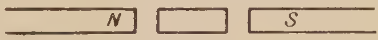


Fig. 20.

Take, by iron filings, a diagram of the lines of force of the field round the magnets *without* the soft iron; then insert the soft iron and again get the magnetic figure; compare it with the former one.

Next get the magnetic figure of a horseshoe-magnet with its keeper on, and compare it with that found in Experiment 15.

Lay a bar of soft iron parallel to, and about 6 cm. from, a bar-

magnet, and obtain the map of the lines of force, comparing it with Fig. 16.

Sketch these figures in your note-book.

19*. A consideration of the results of Experiment 19 will show the student that if a piece of soft iron is put into a magnetic field, the lines of force are disturbed and rearrange themselves so that a great many enter the soft iron at one part and leave it at another; that they behave as if the iron offered to them an easier path than that through the air, so that they will go out of their way somewhat for the sake of traversing the soft iron (just as a man will walk away from his ultimate destination, if by so doing he can get to a railway station on a line running to the place he wishes to reach), a fact that is usually expressed by saying that iron is much more **permeable** to the lines of force than air or any other material.

These lines of force are practically the only evidence we have that a substance is 'magnetized,' so that to say that lines of force enter and emerge from a piece of iron is equivalent to saying that it has south and north poles, whether these 'poles' are permanent or produced by the induction, as in Experiment 19, of the field of force in which it is placed.

It will also be evident that the *mechanical* forces of attraction and repulsion between magnetized bodies can be looked on as being produced by these lines of force. We must imagine that they exert a tension along their length, tending to shorten themselves, at the same time that they tend to swell out sideways so as to thrust away the neighbouring lines. Thus two pieces of iron are attracted together when the lines run from one to the other as in Fig. 17 (iii or v), but repel each other when the tubes from them run alongside one another as in Fig. 17 (iv or vi).

Of course this also explains the attraction of a magnet for a piece of soft iron, as in Experiment 19.

There is no material substance, like india-rubber, present in the space occupied by the lines of force, which is exerting this tension and sideways thrust; but it is supposed that the **ether**, which exists everywhere and is the medium which conveys light and electric effects, is strained along the lines of force in such a way as to produce the same effect on the solids where the lines of force end.

20*. If a sphere or circular disk of soft iron is put in a uniform magnetic field, i. e. one in which the lines of force are all straight and

parallel to one another, as for example that produced by the earth, the field will be distorted as shown in Fig. 21, and from the symmetry

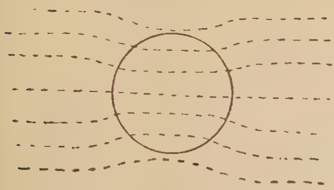


Fig. 21.

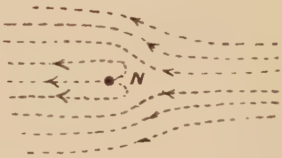


Fig. 22.

of the lines of force they will clearly not exert more pull on one side of the sphere than the other *. If, however, the soft iron sphere is placed

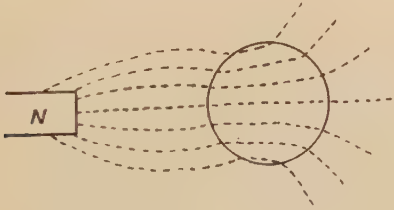


Fig. 23.

in a non-uniform field of force, e.g. near one pole of a bar-magnet, the lines of force will be as in Fig. 23, and the lines of force entering on the left-hand side of the sphere, though equal in number to those leaving on the right-hand side, are better placed for exerting a pull, as they act more in one direction, so that there is a resultant force on the sphere towards the magnet-pole.

* Remember that the lines of force merely try to pull together the solids at their ends, not to push iron along in their own direction; they only do this on a small N. pole, because its own radiating lines of force disturb them as in Fig. 22, where the N. pole is urged to the left by the action between the lines of force.

CHAPTER IV

LAWS OF MAGNETIC FORCE

21. IN order to be able to calculate numerically or mathematically the actual forces exerted by one magnet on another or on a piece of iron, we must begin by considering the case, which cannot be realized in practice, of a pole situated alone in a tiny piece of steel acting on a similar pole in another piece. We can get somewhere near these conditions by using very carefully magnetized long slender steel wires, like elongated knitting-needles, but the forces between the poles at the ends are extremely small *.

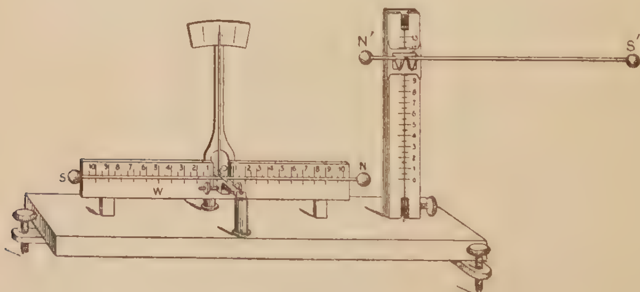


Fig. 23 *a*

* These forces were first measured by Coulomb in 1785 by means of an apparatus called a Torsion Balance, in which one such wire was hung horizontally by a very slender fibre, and near its end, on the E. or W. side of it, the end of the other wire was placed. The force of the second pole, tending to turn the suspended needle round, was balanced by twisting the top end of the fibre until the suspended wire came back into its former position; the force needed to effect this was then calculated from the angle through which the top end of the fibre had been twisted. In spite of the very great difficulties of this experiment, Coulomb got results showing the extent to which the force between two ideal magnetic poles is reduced by an increase in the distance between them, as well as the manner in which the force of attraction or repulsion depends on the strength of the poles.

21a. Hibbert's magnetic balance. The most direct method of measuring the attraction or repulsion between two poles is to support such an elongated needle at its centre, like the beam of a balance, and to hold vertically above one of its ends the end of another magnetized wire, the other pole of which is far enough away not to affect the balanced needle. The best arrangement is shown in Fig. 23 *a*, where $N S$ is the balanced needle, and $N' S'$ the fixed needle, the latter supported on a scale which shows the distance between N and N'. Before $N' S'$ is brought near it, the needle $N S$ is horizontal; when N' is brought up, N is repelled downwards and can be brought back to its former position by putting a weight W on the wire at a point on $N S$ to be discovered by trial. If we know the weight W and its distance ($W O$) from the knife-edge by which $N S$ is balanced, we can calculate the force of repulsion on the pole N. So a series of such experiments with different distances between N and N', will show how the repulsion between two similar poles changes with the distance between them.

EXPERIMENT 19 *a*. **To find the law of force between two poles.** Before bringing up the magnet $N' S'$, note the position of N, of the pointer attached to $N S$, on scale when $N S$ is horizontal. Put $N S$ out of balance by putting W on $S O$, with its centre at some definite distance, say l_1 cm., from C. Fix $N' S'$ in its clip and move it up or down until $N S$ swings an equal distance on each side of its horizontal position, as in weighing with a sensitive balance. Note the distance $N N'$ at which this occurs; call it d_1 cm.

Repeat for another distance of W from O, say l_2 cm.; call the new distance $N N'$, d_2 cm.

Now if F_1, F_2 are the respective forces of repulsion at the distances d_1, d_2, and the length $N O$ is called L cm., and the weight of W is called W, we have by the principles of statics,

$$F_1 \times L = W \times l_1,$$

and $$F_2 \times L = W \times l_2;$$

hence, dividing, $$\frac{F_1}{F_2} = \frac{l_1}{l_2}.$$

So in order to find how F changes with the distance between the poles, we have only to find how d changes with l. If the force varies directly as the distance between the poles, we should have

$$\frac{F_1}{F_2} = \frac{d_1}{d_2}, \text{ i.e. } \frac{l_1}{l_2} = \frac{d_1}{d_2}, \text{ and } l_1 d_2 \text{ would equal } l_2 d_1.$$

Do you find that this is so?

Again, if the law is that the force varies inversely as the distance between the poles, we should have

$$\frac{F_1}{F_2} = \frac{d_2}{d_1}, \text{ i.e. } \frac{l_1}{l_2} = \frac{d_2}{d_1}, \text{ and } l_1 d_1 = l_2 d_2.$$

Do you find that this is so?

If the law is that the force varies inversely as the square of the distance between the poles, we should have

$$\frac{F_1}{F_2} = \frac{d_2^2}{d_1^2}, \text{ i.e. } \frac{l_1}{l_2} = \frac{d_2^2}{d_1^2}, \text{ and } l_1 d_1^2 = l_2 d_2^2.$$

Is this the case?

If you find that for several values of l, the corresponding value of d is such that $l d^2$ is the same, it may be assumed that the law is true that *the force between two poles varies inversely as the square of the distance between them.*

22*. Deflection Magnetometer. By using an indirect method, involving some little theoretical reasoning and a good many assumptions as to the position of the poles in an actual magnet, &c., we can determine by experiment the law connecting the decrease of the force of repulsion with the increase of the distance between the poles. The first assumption we shall make is that *one pole repels or attracts another along the straight line joining them*, i. e. that one pole free to move will be repelled or attracted straight from or towards the other pole.

Suppose that we have a small compass-needle NS (Fig. 24), and that at a point P due E. or W. of its centre O we place a magnet-pole. Let the distance PO be r cm. The pole at P will repel N and attract S, so that NS will be deflected from the north-and-south line. This line is usually referred to as the **Magnetic Meridian**; a full definition

will be given later, but for the present we will consider that it is the line through the poles of a freely suspended compass-needle, which has been allowed to come to rest unaffected by any neighbouring magnets.

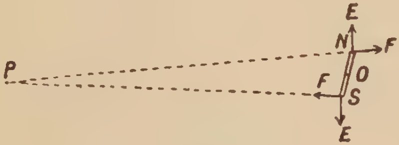


Fig. 24.

If the earth was not pulling the needle back into the magnetic meridian, it would swing round until $S N$ was in a line with P; as it is, it will take up an intermediate position, being deflected through a greater or less angle from the magnetic meridian according as the repulsion of the magnet-pole is large or small. Let us denote the pull of the earth on the poles of the compass-needle by E as in Fig. 24, and the forces * exerted by the magnet-pole on the poles of the compass-needle by F; we will assume that P is so distant from O that the small difference between the lengths of $P N$ and $P S$ produces no appreciable difference between the forces on N and S, and further that the compass-needle is so short compared to the length $P O$ that the lines $P N$, $S P$ along which these forces act may be treated as parallel to $O P$ without appreciable error. These assumptions very greatly simplify the calculations, and in practice the apparatus can easily be so designed that the errors caused by them are negligible.

Consider now the forces acting on N when the needle has come to rest in its deflected position. There is the attraction (E) of the earth acting parallel to the magnetic meridian, the repulsion (F) of the magnet-pole at right angles to this, and some force acting along the needle towards or from the pivot O. We are not concerned with the magnitude of this last force, but only with its direction, which is of course that of the needle. Let this direction be denoted by the dotted line through N in Fig. 25, which shows only one of the poles. Let

* It is here assumed that the two poles at the end of a compass-needle are of equal strength, but the argument would not be affected if this were not the case.

NE and NF represent in magnitude and direction the forces E and F. Then we know by the Parallelogram of Forces that the direction of the resultant of these forces must be that of the diagonal of the rectangle $ENFN'$.

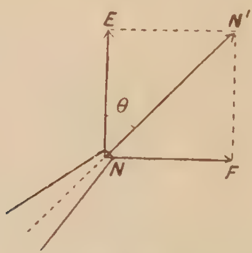


Fig. 25.

Now this resultant must be in a line with the needle, because if not it would pull the needle round into a new position. Therefore the line NN' makes the same angle with the meridian as does the needle.

Let us denote the deflection of the needle from the magnetic meridian by θ; then we must have, also,

$$ENN' = \theta.$$

But the length EN' represents the force F on the same scale as EN represents the force E.

$$\therefore \quad \frac{F}{E} = \frac{EN'}{EN}.$$

Again, by the definition of the tangent of an angle (see p. 294),

$$\frac{EN'}{EN} = \tan\theta,$$

$$\therefore \quad \frac{F}{E} = \tan\theta,$$

$$\text{or} \quad F = E\tan\theta.$$

Exactly the same reasoning, of course, leads to the same result for the south pole of the needle, all the forces and directions being merely reversed.

Now E does not change with the position of the needle, so that we

finally arrive at the result that *the tangent of the angle of deflection of the needle is proportional to the force of repulsion of the pole.*

We will now use this result to determine how the force of repulsion between two poles varies with the distance between them.

EXPERIMENT 20. **Law of force between two poles.** Take a magnetometer, which consists of a very short compass-needle provided with a long pointer whose ends move over a circle marked with degrees. Set it so that the ends of the pointer are at 0°. For the purpose of this experiment there is generally attached to the instrument a metre scale stretching out due E. and W. of the centre of the compass-needle and having its zero end at the pivot.

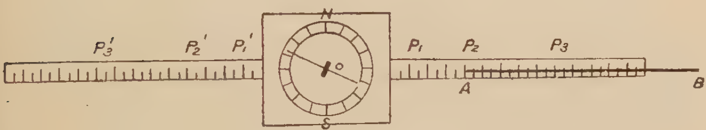


Fig. 26. Magnetometer.

Take a long steel wire, like a very long knitting-needle (not less than 50 cm. long), magnetized so that a pole is situated near each end. The pole will not be exactly at the end, and it is desirable to determine, by means of iron filings, the point near the end towards which most of the lines of force converge, and to consider this as the pole in what follows.

Lay this magnetized wire (as $A\,B$ in Fig. 26) with one pole near the compass-box, at the point P_1. Determine the deflection of the needle, reading each end of the pointer (if the compass-box is provided with a mirror, be careful to place your eye so that the pointer covers its own image as you take the reading); then reverse the needle and fix the same pole A at the point P_1' equally distant from the needle on the other side. This ought to produce a deflection of about the same amount. Observe the deflection as before, and take the average of all four readings as the deflection caused by the pole at the distance OP_1.

In the same way determine the deflections when the pole is at distances twice, and three times, as great as OP_1.

Take the tangents of these three angles from a table of tangents; as shown above, these tangents are proportional to the respective forces of repulsion of the pole A, at distances OP_1, and two and three times as far away.

Now compare these forces: are they in the proportion of 3, 2 and 1? or in the proportion of 3^2, 2^2 and 1^2, i.e. 9, 4 and 1? or $(\frac{1}{1})^2$, $(\frac{1}{2})^2$ and $(\frac{1}{3})^2$, i.e. 9, $2\frac{1}{4}$ and 1? If they are not exactly in any of these proportions, to which set are they most near?

Suppose you have found that they are nearly in the proportion of $(\frac{1}{1})^n$, $(\frac{1}{2})^n$ and $(\frac{1}{3})^n$; you might assume that the law will hold for all intermediate distances, and that 'the force of repulsion of a magnet-pole varies inversely as the n^{th} power of the distance between them.'

To verify this more thoroughly find the average deflections as above when the pole is situated 15, 20, 25, 30, 35 cm. from the centre of the needle; find the tangents of these angles, and fill up a table as follows, of course substituting for n the number you have fixed on.

Distance (r) of pole in cm.	θ	$\tan\theta$	$\tan\theta \times r^n$
15			
20			
25			
30			
35			

If the numbers in the last column are the same within the limits of experimental error * (especially if they vary *irregularly*), you have verified your suggestion as to the law, for you prove that the force (since $\tan\theta$ is proportional to it) decreases in proportion as r^n increases.

* e. g. if the difference between the greatest and least is not more than, say, 5 % of either.

23. Second law of magnetic force. Two magnet-poles may have different *strengths*; this can be seen if we test two magnetized needles, $N_1' S_1'$ and $N_2' S_2'$ say, in Hibbert's balance, putting N_1' and N_2' in succession at the same point and measuring the force each exerts on the pole N. These forces differ, and it is reasonable to compare the strengths of the two poles N_1' and N_2' by these forces; so that the strengths of two poles may be taken as proportional to the forces which they exert on another pole, when placed at the same distance from it, and this serves as a definition of 'pole-strength'.

The complete law giving the forces exerted on each other by two ideal poles is as follows:—

The force between two single magnet-poles is proportional to the product of their strengths, and inversely proportional to the square of the distance between them.

It must be remembered that we cannot in practice get a piece of iron with a single pole, but that we can account mathematically for the behaviour of actual magnets if we imagine their magnetism to consist of a collection of such poles each obeying this law.

Meaning of the law. Suppose that we have a single N. pole free to move, and some means of measuring the force that must be called into play to prevent it from doing so when a magnet is brought near; and suppose that we are provided with one or two single N. poles of exactly the same strength. If one of these poles is brought up to a certain fixed distance from the stationary pole, the latter will be repelled with a certain force; the law states that if another pole of the same strength is put alongside the first, that force will be doubled, and if another pole is added it will be trebled and so on, the increase in repulsion being proportional to the increase in strength of the repelling pole.

Again, according to the law, if the stationary pole is doubled, trebled, &c. in strength, the repulsion exerted on it by a pole at a fixed distance from it will be doubled, trebled, &c.

If then the stationary pole and the pole producing the repulsion are both increased in strength, the repulsion between them will be always proportional to the *product* of their strengths.

Now confining our attention to the force of repulsion between two poles whose strength is constant, the law states that if the force is represented by F when the distance between the poles is, say, 1 cm., it will be $\frac{1}{2^2}F$ or $\frac{F}{4}$ when the distance is 2 cm.; $\frac{1}{3^2}F$ or $\frac{F}{9}$ when the distance is 3 cm., and so on; 2^2F or $4F$ when the distance is $\frac{1}{2}$ cm.; 3^2F or $9F$ when the distance is $\frac{1}{3}$ cm., &c.

We can state the law in symbols thus: Suppose the strengths of the two magnet-poles are m, m' units respectively, and the distance between them is r cm., then the force between them is proportional to

$$\frac{m\, m'}{r^2}.$$

24. Explanation of magnetic figures. The second law of magnetic force enables us to account for the shape of the lines of force in a magnetic field. Consider for example that round a bar-

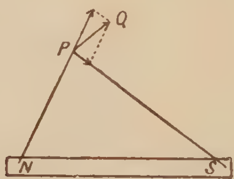


Fig. 27.

magnet. The forces on a N. pole at P in Fig. 27 will consist of a force along NP and one along PS; these will have a resultant, as PQ, and that will be the direction of the line of force at P.

By measuring the distances NP and PS the *relative* magnitudes of the forces along NP and PS can be calculated by the second law. This is all that is needed in order to find the *direction* of PQ; so that the direction of the force at every point of the field can be calculated, and the result compared with the magnetic figures obtained as in Experiments 15 and 16.

25*. Unit pole. We have not yet fixed on our unit strength of pole, and we can now see what will be most convenient. **A magnetic pole is of unit strength when it repels an exactly equal pole placed at a distance of 1 cm. with a force of 1 dyne** †.

If m and m' express the number of these units in the poles, the expression $\frac{m\, m'}{r^2}$ in Art. 23 becomes *equal* to the force (F say) measured in dynes between the poles, instead of merely proportional to it, so that we have

† A dyne is the absolute unit force on the C. G. S. system, and is the force which is needed to produce in 1 gram. an acceleration of 1 cm. per sec. per sec.

$$F = \frac{m\,m'}{r^2} \text{ dynes.}$$

In the above statement m and m' are supposed to be + if they are N. poles, − if S. poles, and F to be a repulsion if it is $+^{ve}$ and an attraction if $-^{ve}$.

The number of units in the pole of a long slender magnetized needle can actually be measured by means of Hibbert's balance.

Call it m units; call the strength of the pole of the needle in the balance, m_1, and take another needle of pole strength m_2. Put m and m_2 successively at the same distance (d cm.) from m_1, and find the distances (l and l_2 cm.) of the sliding weight (M grms.) from the knife-edge when balance is restored in each case. Calling F and F_2 the forces between m and m_1, and m_2 and m_1, respectively, we have

$$F = \frac{m\,m_1}{d^2} \text{ and } F_2 = \frac{m_1\,m_2}{d^2}$$

$$\text{and } \frac{l}{l_2} = \frac{F}{F_2} = \frac{\dfrac{m\,m_1}{d^2}}{\dfrac{m_1\,m_2}{d^2}} = \frac{m}{m_2} \quad . \; . \; . \; . \; . \; . \; . \; . \quad \text{(i)}$$

Next balance the needle whose pole is m instead of the one already there, and fix the needle whose pole is m_2 at distance d cm. above it; call l_3 cm. the new distance of the sliding weight when balance is restored. Then by principles of mechanics we have, if F_3 is the force of repulsion between m and m_2, and L cm. is the length of NO_1, $F_3\,L = Mg\,l_3$.

$$\text{But } F_3 = \frac{m\,m_2}{d^2}, \text{ so } m\,m_2 = \frac{Mg\,d^2\,l_3}{L} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad \text{(ii)}$$

Hence from (i) and (ii) $m^2 = \dfrac{Mg\,d^2\,l_3\,l}{L\,l_2}$, and all the quantities on the right can be found, so m can be calculated.

26*. Axis and magnetic moment of a short magnet. The bar-magnets ordinarily used are 'short,' that is, their length is not more than about ten times their breadth, and for practical purposes the influence of the more distant pole can by no means be neglected.

If the lines of force surrounding such a bar-magnet are traced, there will be found a point at each end towards which a majority of the lines tend; these points may be considered to be 'the poles' of the magnet.

The straight line joining the poles of a magnet is called the **axis of the magnet.**

The product of the strength of either of the poles of a magnet into the distance between its poles is called the **magnetic moment of the magnet.**

The pole strength must be measured in the units defined in Art. 25, the distance in cm.; and the value of the magnetic moment is usually denoted by M, no name being given to the unit of magnetic moment.

To measure the magnetic moment of a short magnet.

Let NS in Fig. 28 represent a short bar-magnet, of length $2\,l$ cm.,

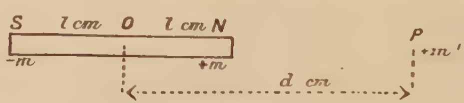


Fig. 28.

having poles of strength m units at N and S. Then its magnetic moment $M = 2\,lm$.

Suppose that a magnet-pole of strength m' units is situated at a point P in the line of the axis of the magnet, and at a distance of d cm. from the *centre* (O) of the magnet.

Then the length PN is $(d-l)$ cm. and PS is $(d+l)$ cm.

Therefore the force of repulsion by N of the pole at P is

$$\frac{m\,m'}{(d-l)^2} \text{ dynes},$$

and the force of attraction by S of the pole at P is

$$\frac{m\,m'}{(d+l)^2} \text{ dynes}.$$

Therefore the resultant force on P is a repulsion of

$$\frac{m\,m'}{(d-l)^2} - \frac{m\,m'}{(d+l)^2} \text{ dynes};$$

or $$\frac{m\,m'}{(d-l)^2\,(d+l)^2}\left\{(d+l)^2 - (d-l)^2\right\} \text{ dynes};$$

or $$\frac{m'\,m}{(d^2-l^2)^2}\left\{4\,d\,l\right\} \text{ dynes};$$

or $$\frac{4\,m\,l\,.\,m'\,d}{(d^2-l^2)^2} \text{ dynes};$$

or $$\frac{2\,M\,m'\,d}{(d^2-l^2)^2} \text{ dynes}.$$

Now suppose the magnet NS is lying E. and W., and that at P is

placed a small compass-needle, with a pole strength of m' units at each end. It was shown on p. 24*b* that, if E denotes the attraction of the earth's magnetic force on the north pole of the compass-needle, and θ the angular deflection of the needle from the magnetic meridian, the repulsion on the N. pole is

$$E \tan \theta;$$

$$\therefore \quad \frac{2 M m' d}{(d^2 - l^2)^2} = E \tan \theta.$$

Let H denote the force in dynes which the earth exerts on one unit N. pole; then

$$E = H m',$$

$$\therefore \quad \frac{2 M m' d}{(d^2 - l^2)^2} = H m' \tan \theta,$$

$$\therefore \quad M = \frac{(d^2 - l^2)^2}{2 d} H \tan \theta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(A)}$$

The value of H at Kew is given on p. 39; all the other quantities in this expression can be measured. As a rough approximation the value of H in England may be taken as ·18. ·18

EXPERIMENT 21. **To measure the magnetic moment of a magnet.** Set up a magnetometer as described in Experiment 20, and place the magnet whose moment is required on the metre scale, so that it lies E. and W. at such a distance from the needle as to produce a satisfactory deflection. Read both ends of the pointer; reverse the magnet end for end so that its centre is at the same distance from the needle as before, and again read the deflection. Now put the magnet on the other side of the compass-box at the same distance away, and read the pointer with the magnet pointing in each direction. Take the average of all these eight readings for the deflection; observe d and l and calculate M by means of the above formula.

The observations should be repeated with a different value of d, and the value of M again calculated.

EXPERIMENT 22. **Rough verification of the value found for** M. In Experiment 16 it was shown that due north of a magnet, placed horizontally with its axis in the magnetic meridian and its N. pole towards the south, there is a point where the needle of an exploring compass will rest in any direction. This point can of course be very rapidly found, without drawing any of the lines of force, by moving the exploring compass due N. from the magnet

until the needle reverses. At this point the force of the earth just balances that of the magnet; with the letters used above,

$$\frac{2\,M\,d\,m'}{(d^2 - l^2)^2} = H\,m',$$

$$\therefore \quad M = \frac{(d^2 - l^2)^2\,H}{2\,d},$$

where d cm. is the distance of this 'neutral point' from the centre of the magnet, and $2\,l$ cm. is the length of the magnet.

Check the value of M found in Experiment 21 in this manner. The exact position of this neutral point cannot, of course, be found very accurately.

27. Method of oscillations. Suppose that a small magnet is suspended horizontally in a magnetic field, either on a pivot through its centre as in a compass, or by a fibre as in Experiment 2; then if it is disturbed from its equilibrium position, so that each of its poles describes part of a circle round its centre which remains at rest, the magnet will continue to oscillate for some time on each side of its equilibrium position. Each swing will be a little smaller than the last, but will be performed in the same time; in fact the magnet behaves exactly like an ordinary pendulum which swings under the action of gravity.

The time of swing of a given magnet depends on the strength of the field of force in which it hangs; the law connecting them is similar to that for a pendulum, and may be proved to be as follows: *The square of the number of oscillations made in a given time by a magnet is proportional to the magnetic force at the point.*

The actual time of swing depends on the magnetic moment of the magnet, on its mass and on the manner in which that mass is distributed along the magnet, as well as on the magnetic force at the point of suspension; but so long as we keep to the same magnet all but the last will be constant, so that we can easily *compare* the magnetic forces at two points by counting the number of times a magnet swings backwards and forwards in, say, a minute at each of the points in succession; dividing one of these numbers by the other, and squaring the result, we have the ratio between the magnetic forces at the respective points*.

EXPERIMENT 23. **To compare the magnetic forces at different points.** Take a small 'oscillating magnet,' such as a piece of magnetized knitting-needle about 1 cm. long hung by a silk fibre, or

* See Appendix E.

better a loaded needle as described in the Appendix, p. 289. Suspend it from a non-magnetic stand, and if necessary shade it from draughts by hanging it in a glass case, such as a small beaker. Set the magnet swinging slightly backwards and forwards by means of another magnet-pole, being careful to avoid *pendular* swinging; count the number of oscillations it executes in a considerable interval, or better, by measuring the time occupied by fifty or a hundred swings, calculate the exact number it would execute in a minute. Now repeat this in various positions in the laboratory; the number will be found to vary to an easily measurable extent.

If possible repeat the same experiment out in the open, or in some place far removed from the influence of iron gas-pipes, &c., so that the value of H there may be known from Tables of the Magnetic Elements, as described on p. 39.

Suppose n swings per minute are executed at a point where the value of the force is known to be H, and that at another point n_1 swings are made per minute; then the force at the second point is

$$H\frac{n_1^2}{n^2}.$$

This determination is of great importance in finding the Reduction Factor of a Galvanometer (cf. p. 85).

In this manner you can compare the forces at various points in the line of the axis of a long bar-magnet placed in the meridian, and so verify the Second Law of Magnetic Forces, by testing the truth of the formula of Art. 26.

CHAPTER V

Terrestrial Magnetism

28. In Experiment 2 it was found that a magnet, when freely suspended so as to lie horizontally, turns so that it points about north and south. The actual line at any place along which an indefinitely slender magnet would thus set itself, or the line along which the Magnetic Axis (p. 27) of any magnet thus suspended sets itself, is called the Magnetic Meridian there. The name, magnetic meridian, is more properly given to the *vertical plane through this line.*

If we have a really slender compass-needle, the straight line joining its ends is a very near approximation to its Magnetic Axis, and with

it the direction of the magnetic meridian can very easily be found. We may find it even more accurately with a bar-magnet, or even with a circular disk of steel which has no ends to mark its poles.

EXPERIMENT 24. **The magnetic meridian.** Stick pointed pieces of gummed paper on the ends of a bar-magnet, as in Fig. 29.

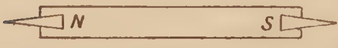


Fig. 29.

Support the magnet with its face horizontal, as in Experiment 2, so that the paper pointers are on the top of the magnet. Fix with pins, in which there is no steel or iron, a piece of paper to the table below the magnet, and adjust the magnet so that it hangs just above the paper. When the magnet comes to rest, mark on the paper the point vertically below the tip of each piece of paper.

If the magnet takes a long time to come to rest, mark the extremities of a swing about its position of equilibrium; join these points to form an acute-angled cross and bisect the acute angle between these lines; this will be the line of rest of the magnet under the earth's attraction ($A\,A'$ in Fig. 30).

If the line joining the tips of the paper pointers happens to be the magnetic axis of the magnet you have found the magnetic meridian; but it is very unlikely.

Fig. 30.

Now turn the magnet upside down in its stirrup so that the paper pointers are underneath. Repeat the experiment; you will obtain another line on the paper fixed on the table ($B\,B'$ in Fig. 30).

In both of these positions the magnetic axis of the magnet must point in the same direction, since it always lies in the magnetic meridian however the magnet hangs; by turning the magnet over, the line joining the tips of the paper pointers must have come into a position on the other side of this line of the magnetic meridian, and equally inclined to it. Hence by bisecting the angle between $A\,A'$ and $B\,B'$ you will find the true magnetic meridian ($N\,S$ in Fig. 30).

This experiment can be performed even if the magnet is a circular disk.

By letting the magnet come to rest over the line $N\,S$ you can determine the actual position in the magnet of its magnetic axis, since it lies vertically over $N\,S$.

29. Geographical meridian. The plane passing through the axis (of rotation) of the earth and any place on its surface is called the **geographical meridian** of that place.

Since we only know the position of the axis of the earth by observing the apparent motions of the fixed stars, we can only find the geographical meridian of any place by astronomical observations. If we follow the movement of a star, planet, or the sun during a day, we see that it rises in the heavens until it reaches a maximum elevation and then begins to sink; the point where it stands highest is the point at which it crosses the geographical meridian.

If the star or sun is bright enough to cause an upright stick to cast a shadow that shadow will be shortest when the star or sun reaches its greatest altitude; hence we can find the geographical meridian by watching the shadow of an upright stick and marking its position when it is shortest.

As the length of the shadow changes very slowly when the sun is near to the meridian this method will not lead to an accurate result; but we can modify it slightly in order to do so.

EXPERIMENT 25. **To find the geographical meridian.** Set up a vertical stick on a smooth horizontal piece of ground, or table in front of a window facing south; or slope a stick to the northward and hang a weighted piece of string from its top end (as in Fig. 31), with the weight (O) nearly touching the ground.

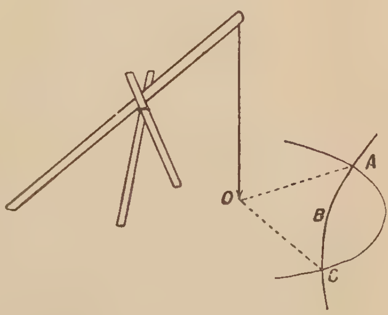


Fig. 31.

At intervals of a few minutes from about 11.30 a.m. till about 12.30 p.m. (if the sun is the heavenly body whose meridian position is to be determined) mark on the ground the end of the shadow cast by the stick, and join these by the curve ABC.

With centre O draw a circle cutting the curve in two points, A and C. Join OA, OC and bisect the angle between them by the line OB.

This is the true north-and-south line in which the geographical meridian cuts the earth's surface.

30. Magnetic declination. If the geographical and magnetic meridians are determined at any place they will be found to lie in somewhat different directions. The angle between them is called the **magnetic declination** (or 'Variation,' in Navigation) at that place.

A knowledge of the exact value of this angle is obviously of the greatest importance to navigators, since they need to know the true north, and their compass indicates magnetic north; unfortunately it changes at any place from year to year, and at any time it is different at different places. These changes of the declination have been accurately observed and do not occur erratically; hence they may be predicted for a given place at a given date with fair accuracy from a knowledge of the value of the declination at a number of neighbouring stations for several years previously. On all charts the value of the declination at each place is stated for a certain date, together with its annual increase or decrease; hence the declination for that place at any subsequent time can be determined.

The values of the declination at Greenwich are shown in the following table. It is now W., i.e. the compass points to the west of true north.

DECLINATION AT GREENWICH.

Year.	Declination.
1580	11° 17′ E.
1622	6° 12′ E.
1660	0°
1720	13° 0′ W.
1816	24° 30′ W. (max.)
1890	17° 30′ W.
1900	16° 29′ W.

At present it decreases at the rate of 6′ 2″ per annum. The declination will again be zero at London, i.e. the compass will point due north, about 1975. The declination increases as one goes W. from Greenwich, and decreases towards the E. In 1900 it had the following values:—

Plymouth	18° 15′ W.
New York	9° 12′ W.
St. Petersburg . . .	0° 30′ E.

31. Magnetic maps. Just as curves are drawn to embody the results of a large number of experiments, so lines may be drawn on maps to show at a glance the value of the magnetic declination at any place. The system adopted is to draw a line running through all places where the magnetic declination is the same, in the same way as contour lines are drawn through all points at the same height above sea-level; a large number of such lines are drawn, say one for each degree of declination, and then the value of the declination at a point which does not lie on one of these lines can be approximately ascertained from its distances from the lines on each side of it.

32. Magnetic dip. In 1576 a scientific-instrument maker named Norman discovered that if he magnetized compass-needles *after* they were correctly balanced on their support, the north pole hung down and the south pole had to be weighted to restore the level of the needle. He was thus led to make a compass-needle of a piece of steel, supported so that it could turn freely about a *horizontal* axis which passed through its centre of gravity; before it was magnetized it would rest in any position, but after magnetization its north pole pointed downward about 72° below the horizontal.

This 'dipping' can be best observed by using a flat pointed strip of steel with an axle through its centre, such as is provided in the more simple forms of 'dip-circles'; this should be freely supported in a stirrup of thick brass or copper wire bent as in Fig. 32 and hung from a support by a fibre of unspun silk. If the needle is unmagnetized it will rest in any position; but if magnetized the needle will finally settle down so that its axle points east and west (magnetic) and its north pole dips down at an angle of about 67° below the horizontal.

Fig. 32.

EXPERIMENT 26. **To measure the dip by a dip-circle.** A dip-circle is an instrument consisting of a vertical circle graduated in degrees, with a needle as described above mounted on bearings so that its axle is horizontal and at the centre of the graduated circle.

If the axle passes exactly through the centre of gravity of the magnet, and the magnetic axis is the line joining its ends, and if the scale is exactly accurate, all that you need do to determine the dip is to place the plane of the circle in the magnetic meridian with the

help of a separate compass, and read the position of the point of the needle.

These conditions of course cannot be realized in practice, but the errors due to their absence can be eliminated as follows. After the dip-circle has been set so that the vertical plane in which the needle swings coincides with the magnetic meridian, readings of the position of both ends of the needle are taken; then the needle is reversed in its bearings so that the face that was outward is now towards the graduated circle, and the position of both ends of the needle is observed. The dip-circle is now turned through two right angles, so that the side previously towards the east now faces west, and these four readings are again taken.

The needle is now removed and carefully re-magnetized by the method of double touch (p. 13) or otherwise, so that its polarity is exactly reversed, thus making the other end of the steel dip. The eight readings are again made as before.

The average of the sixteen readings gives the dip.

The method of placing the face of the circle in the magnetic meridian that is adopted in accurate work is as follows. The dip-circle is turned until the needle stands exactly vertical under the earth's force; it must then be so situated that the horizontal axle of the needle is exactly in the meridian; then if the dip-circle is moved round through a right angle, the axle of the needle will point magnetic east and west. For this method the dip-circle is movable about a vertical axis in its base and carries a pointer moving over a horizontal graduated circle.

33. Changes in dip. As with the declination, the value of the dip at any place changes from year to year, but more slowly. The following table gives the value of the dip at Greenwich for some years:—

Year.	Dip.
1576	71° 50′
1676	73° 30′
1720	74° 42′ (max.)
1876	67° 46′
1900	67° 9′

The dip is now decreasing at the rate of about 1·6′ per annum.

The value of the dip differs very largely from place to place on the earth's surface. There is a line, which runs roughly along the Equator, called the line of No Dip; at any place on it the dipping-needle lies horizontally. To the north of this the north end of the needle dips, to the south of it the south end of the

needle points downwards. If a magnetic map be prepared showing a series of lines each running through all points on the earth's surface where the dip is the same, these lines are roughly parallel to the parallels of latitude. As you proceed to the north the dip increases, until at a point in the NE. of Canada (Boothia Felix) the dip is 90°, i. e. the needle stands upright. This point was reached by Sir James Ross in 1831; it is called the North Magnetic Pole. Its position was about 1,400 miles from the true North Pole, in Lat. 70° N., Long. 96° 43′ W.

The South Magnetic Pole was reached in 1909 by Sir E. Shackleton's expedition. Its position was in South Victoria Land, about 1,200 miles from the true South Pole, in Lat. 72° 25′ S., Long. 155° 16′ E.

In 1900 the dip at London was 67° 9′, at Edinburgh 70° 20′, at Lerwick, in Shetland Isles, 72° 36′.

34. Magnetic condition of the earth. If the position of the dipping-needle is marked for a number of places lying along a meridian of longitude of the earth, the result will be somewhat as shown in Fig. 33; the meridian chosen is that passing through Boothia Felix.

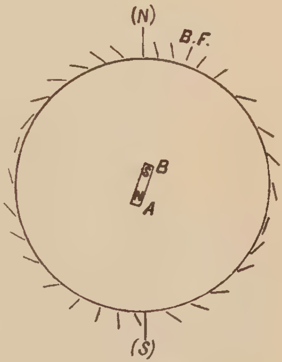


Fig. 33.

If on the same diagram the lines of force be drawn, surrounding a *short* bar-magnet AB at the centre of the earth, placed with its south pole pointing to Boothia Felix ($B.F.$), these lines of force will cut the surface in directions approximately those found for the dipping-needle at the respective places. Hence, although the minor variations point to a much more complex distribution of magnetism, we may say roughly that the earth acts as though it had a very short and very powerful magnet at its centre. Since the temperature at the centre is probably far above red heat, there is little doubt that no such magnet exists there. This magnetic effect may be due in part to permanent magnetization of the materials in the surface of the earth where it is not at too high a temperature, in part to electric currents circulating in the earth itself, and in part to electric currents circulating in the atmosphere, especially in the upper levels

where the air is very rare and in consequence readily permits the flow of electricity (p. 257).

This supposition is supported by the changes in the magnetic effects on the surface; not only are there the changes above described, but daily and hourly variations of an irregular kind, such as might be expected in consequence of changing atmospheric conditions; a connection has often been traced between these variations and the outburst of spots on the sun, the position of the sun and moon with respect to the earth, &c.

35. Total force. Let NS in Fig. 34 represent the dip-needle in its position of rest; the magnetic force of the earth on the N. pole must lie along the line ON. Let us assume that the needle has a unit magnetic pole at each end, and let the force (measured in dynes, see p. 26) of the earth on each pole be called T.

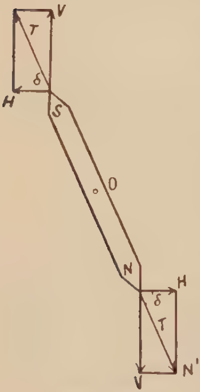


Fig. 34.

Draw a line NN' as in Fig. 34 of such a length as to represent the force T on a convenient scale. Through N and N' draw horizontal and vertical lines making a rectangle. Now we may consider that the pole N is acted on, not by one force T, but by two forces, one vertical the other horizontal, provided these be chosen of the right magnitude; and in order to have a resultant represented by NN' we know by the Parallelogram of Forces that these two forces must be of magnitudes represented, on the same scale, by the vertical and horizontal sides of the rectangle. Call these two components V and H.

Then if the dip be $\delta°$ we have $\dfrac{V}{H} = \tan\delta$,

and $$T = \sqrt{V^2 + H^2}.$$

The same reasoning of course applies to the south pole S of the needle.

The magnetic force most commonly used is the horizontal component H; the total force of the earth on a unit magnet-pole, as well as the vertical component, can be obtained by the above equations from a knowledge of the value* of the horizontal component (H) and the dip (δ).

* See Appendix (p. 296).

36. Total force and horizontal force. The value of the total magnetic force of the earth, like the declination and the dip, varies from time to time and from place to place.

At any one place the most important thing to know is the horizontal force H. Its variation at Kew is shown in the following table:—

Year.	H.
1860	·1755
1870	·1779
1880	·1798
1890	·1817
1900	·1836.

The change from place to place of the total force is considerable; for example, at Greenwich ·472, Edinburgh ·484, Boothia Felix ·65, New York ·61, St. Helena ·31, Sydney ·57.

37. Magnetization of a bar of iron by induction in the earth's magnetic field. If a bar of iron such as a poker, or a long strip of tin-plate, is held parallel to the lines of force of the earth (i. e. in the plane of the magnetic meridian and dipping downwards at an angle about 70° below the horizontal) it will be magnetized feebly by induction, just as it would in any other magnetic field. This can be observed if its lower end is brought close to a compass-box E. or W. of the needle; the lower end of the bar will be found to have a N. pole (if the observation is made in the northern hemisphere), the upper end a south pole, and these poles reverse in the bar as the bar is turned end for end. The bar must be struck by a hammer while under induction, in order to allow the molecules free play (cf. p. 12).

If the bar is held vertically, only the vertical component V will affect it; if horizontally, only the more feeble component H, and the north end of the bar will acquire a N. pole.

With such a bar and magnetometer we can determine, somewhat roughly, the value of the dip; for the strength of the magnetic poles induced in the bar may be assumed to be proportional to the strength of the component parallel to the bar, and the strength of the poles may be compared by the method of Experiment 20, so that the value of $\frac{V}{H}$, i. e. of tan δ, may be determined.

EXPERIMENT 27. **To measure dip by magnetic induction in a soft iron bar.** Take a long bar of soft iron; hold it vertically and hammer it on the end; keeping it vertical bring its lower end on to

the metre scale of a magnetometer at a convenient distance due E. of the compass-needle, and then due W. of the needle at the same distance from it. Observe the average deflection (θ_1) of the magnetometer-needle in the two cases (of course reading each end of the pointer and taking the average of the four readings).

Now hold the bar *horizontally, in the magnetic meridian*, and hammer it as before. Bring its north end to the same distance from the compass-needle as before, first one side then the other (keeping the bar horizontally and in the meridian), let the average deflection of the needle be θ_2.

Then, as in Experiment 20, the strengths of the poles in the bars in the two cases are in the same proportion as tan θ_1 to tan θ_2;

$$\text{i.e.}\quad \frac{V}{H} = \frac{\tan\theta_1}{\tan\theta_2},$$

$$\therefore\quad \tan\delta = \frac{\tan\theta_1}{\tan\theta_2}.$$

Hence δ may be found.

PART II

VOLTAIC ELECTRICITY

CHAPTER I

THE ELECTRIC CURRENT

38. THE ordinary method of preparing the gas called Hydrogen in a chemical laboratory consists in putting pieces of a metal, zinc, into sulphuric acid; an effervescence occurs and the gas can be collected. This appears to be a very simple process, and to have little connection with electricity; but we can take it as our starting point in investigating electric currents.

Let us then try and find out the conditions governing the chemical changes that go on when zinc is dissolved in sulphuric acid, making experiments that will show the factors which help and hinder the process.

EXPERIMENT 28. Take a strip (about 2×10 cm.) of ordinary 'commercial' sheet zinc, such as is often used for the gutters on a roof. If its surface is dirty, clean part of it with emery cloth; you should always have some of this at hand when doing electrical experiments.

Take also some sulphuric acid diluted with water. For such a purpose, 1 part by volume of acid to 40 parts of water is quite strong enough; for batteries, 1 part acid to 10 parts water is better.

Put the strip of zinc in the dilute acid, leave it for some minutes and record in your note-book all that happens.

39. What you observe is the evidence of the progress of a *chemical change*; sulphuric acid is a compound formed of three elements, hydrogen, sulphur, and oxygen, and when this chemical change goes on, the zinc dissolves in the acid and turns out the hydrogen. If you leave it long enough the process goes on until all of the zinc or acid is used up: if you have plenty of zinc, a fluid is left which is not sulphuric acid and water, but water containing zinc

sulphate dissolved in it, and if the water is driven off by heat, the zinc sulphate is left as a white powder.

If you take more acid than is needed to dissolve the zinc, all the zinc disappears into the liquid, but there is left a black mud which is composed of the 'impurities' contained in the zinc, such as minute particles of iron and arsenic. These impurities do not make the zinc less useful for 'commercial' purposes, hence they are not extracted before the zinc is made into sheets, as this involves trouble and expense. Pure 'redistilled' zinc can, however, be bought, and is usually free from these impurities.

EXPERIMENT 29. Repeat Experiment 28, using pure instead of commercial zinc. Record what you observe, comparing carefully in the two experiments the amount of effervescence, and the state of the surface of the zinc after it has been in the acid for some time.

The different results of these two experiments will probably suggest to you that the chemical action is at least assisted by the impurities, since much less effervescence takes place from pure zinc in sulphuric acid than from commercial zinc.

40. You might expect that if you could get perfectly pure zinc without any impurities at all, absolutely no chemical action would take place, and that the acid would not attack it any more than it seems to attack the glass vessel. This, however, would not be a justifiable conclusion from your experiment; and, as a matter of fact, some action would probably take place, because the zinc is cast into its shape and crystallizes in cooling. The resulting difference in hardness between different parts of the zinc seems sufficient to help chemical action to begin.

You have, however, proved that impurities do help the action, and must now investigate the reason.

First make experiments with a 'foreign body' on a large scale.

EXPERIMENT 30. Take a piece of copper, or one of carbon *, dip it in dilute sulphuric acid and look out for bubbles. Do not be misled by air-bubbles carried down on the surface; if there are any, brush them off, and be sure that the bubbles *grow* under the surface before you believe that any chemical action takes place. Make up your mind as to whether the acid acts on copper (or carbon).

* This is kept in physical laboratories in rods or sheets, and is got from the insides of gas retorts after they have been used many times for making gas: it is a very hard form of the same substance as charcoal, black lead, and diamonds.

Take out the copper (or carbon) and put in the pure zinc, which must be so pure that only a few bubbles rise from it.

Next put in the copper or carbon, taking care that it does not touch the zinc, and carefully observe whether the presence of the 'impurities' in the acid with the zinc helps the chemical action between the zinc and the acid. When you have recorded the result, make the zinc and the copper touch one another underneath the acid, and notice any effect.

Of course in all such experiments you must carefully describe in your note-book *all* that you have observed to happen—not what you think ought to happen, or a few of the things that happen.

41. Your last experiment would suggest that when pure zinc and an 'impurity' touch one another underneath acid, since bubbles arise from the 'impurity' and not from the zinc, the acid must be attacking the impurity which it previously failed to attack. But this is hard to reconcile with what you saw in Experiment 28, that, when the impurity and the zinc were intimately mixed, the acid dissolved the zinc, and the 'impurity' was left as mud.

It is clearly necessary to determine for certain which of the two is attacked by the acid: we can easily do this by weighing each before and after the experiment.

EXPERIMENT 31. Clean, dry, and weigh a piece of pure zinc and a piece of copper; put them into a beaker of dilute sulphuric acid, so that they touch one another, and so that bubbles stream up from the copper. Leave them thus for five or ten minutes; then rinse each with water; dry, and weigh again. Record the weights and the time during which the action went on.

42. While this action is going on we can try whether the same effervescence will rise from copper or carbon if it touches the zinc in any other way.

EXPERIMENT 32. Take a piece of pure zinc, dipping into dilute sulphuric acid. Touch the part *outside* the acid (as in Fig. 35) with a piece of copper, and note if chemical action is increased thereby.

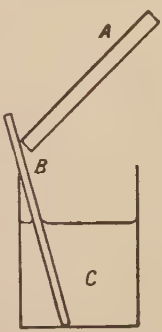


Fig. 35.

Now interchange the zinc and copper. See whether the mere contact of zinc helps the acid to act on the

copper. Next dip *both* into the acid, and make them touch one another outside the acid (as in Fig. 36) and note the effect.

Be careful to make the contact really good, by pressing them firmly together with a slight scraping movement, and in each case give bubbles plenty of time to form.

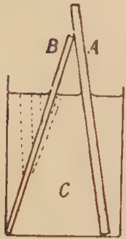


Fig. 36.

To sum up, these experiments should show you that if pure zinc and an impurity, such as copper or carbon, touch one another while both are in contact with dilute sulphuric acid in a vessel, the zinc is eaten away and a gas (hydrogen) appears on the surface of the impurity. (It has not been proved that no chemical action occurs if the zinc and impurity are dipped into *separate* vessels of acid while touching outside ; you can easily try this.)

Thus we can picture what is happening at the surface of commercial zinc in acid. Fig. 37 is a much exaggerated view of such a piece ; the gas rising from the impurity (A), not from the pure zinc (B), which latter, however, is eaten away.

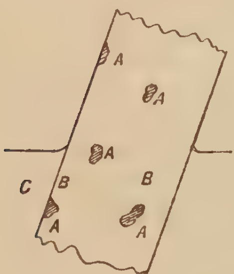


Fig. 37.

This view of the case explains what you should have noticed in Experiment 28, that the effervescence becomes more violent after the action has gone on for some time, because, as the zinc gets dissolved away, more impurities are left on the surface.

43. We have not in any way as yet arrived at an explanation of *why* the impurity helps on the action, and it is here that 'Electricity' comes into play.

Experiment 33. Dip the zinc and copper strips into the acid, so that they do not touch one another at any point, and then join them, by touching both simultaneously with some third substance, such as a penny. Notice if chemical action takes place, as shown by effervescence from the copper. Try this with several substances, such as a wooden pencil, a knife-blade, a piece of paper, and any other materials you have at hand. Make a list of *materials* (e.g. 'steel,' not 'knife-blade') according as they are effective or non-effective in joining the zinc and copper.

You will find that any metal is effective, and most other sub-

stances are ineffective; the question obviously worth following up is, what is going on in the metal while it is assisting the chemical action?

44. For experimenting on this, it is convenient to have the connecting metal in the form of a thin wire which can be attached to the plates by metal clamps called 'binding screws.' One of the great advantages of such screws is that the act of screwing up rubs any dirt from the surfaces and brings the metals into good contact. The best wire for the purpose is made of copper, and it is usually wrapped over with a covering of cotton, the advantage of which will be seen later. This covering must be stripped off the end where it has to be put into a binding screw, which can readily be done by scraping the wire with a knife.

Experiment 34. Connect the plates of zinc and copper by a piece of wire about a metre long, and put the plates into the acid. The effervescence will go on, but you will probably fail to perceive any effect on the wire. If, however, you put on the table a pocket-compass, or a compass-needle freely supported in any way, and hold above and parallel to the needle a straight length of the wire, you will find that the needle is affected; it moves as you bring up the copper wire, swinging a certain distance to one side, and then after swinging backwards and forwards awhile, settles down (if the wire is held steady above it) in a different direction from that occupied before the wire was brought to it.

As the same sort of thing occurs if you bring a knife-blade near the needle, it is necessary to test whether the copper wire alone, when it is not joining the zinc and copper in acid, will produce the same effects. Try with a disconnected copper wire whether you can produce any effect at all on a compass-needle without touching the needle. Also try whether the copper wire connected to one plate only, even when both plates are in acid, will affect the needle.

This experiment was first made by Oersted, of Copenhagen, in 1819. It does not show that the copper 'becomes a magnet'—you will not find any part of the copper wire where there are magnetic poles, i.e. from which lines of magnetic force (see p. 16) start out; the compass-needle is not attracted to any point of the copper, but merely tends to turn at right angles to the wire wherever it is, showing that the lines of force are everywhere at right angles to the

copper wire. Thus the field of magnetic force round the wire is quite different from any produced by a permanent magnet.

This experiment shows that just so long as the wire is helping to produce chemical action, it is in some way in a different condition from ordinary copper wire. This fact is expressed by saying that an *electric current is flowing along it.*

Remember that we have merely given a name as a convenient way of referring to this phenomenon; it does not explain it or suggest that we understand what is going on in or around the wire. An enormous number of other experiments have been required to throw any light on this; it may be found convenient to have a rough idea of the theory that has been based on these experiments. According to this theory, a wire made of a metal such as copper consists of an immense number of exceedingly minute particles, called Atoms; each of these particles consists of a central 'nucleus' and a number of still smaller particles, called Electrons. The number of these electrons in each atom varies according to the material; the atom of copper has 29 of them.

The nucleus of a copper atom differs from that of an atom of another substance, but the electrons in the atoms of all substances are similar. Each electron contains a definite quantity of negative electricity; the nucleus contains a quantity of positive electricity sufficient to balance or neutralize the negative electricity of the electrons in its atom; for example, the copper nucleus contains a quantity 29 times as large as that in a single electron. In a solid, each nucleus is fixed in position, but some at least of the electrons often break out of their atom and plunge into a neighbouring atom. If a force acts on all these electrons during their free flight between atoms, urging them all in some one direction, their paths will be deflected, and as they contain electricity, their general movement in one direction will produce an electric current.

From each electron there proceed 'lines of electric force' (see p. 207) throughout the surrounding 'ether'; these lines of force move as the electron moves, and when these lines pass through a compass needle they exert a force on it.

Further information about electrons will be found in Chap. XVI.

45. Local action. We have now given a name to the process by which the impurities in commercial zinc help the acid to attack the zinc: an 'electric current' passes between the impurity and the zinc so

long as the action goes on. If our object be to produce hydrogen this is excellent; but an electric current to be available, must be outside, and not in the substance of the commercial zinc, and any current between the impurity and the zinc leads to a wasteful chemical action which uses up the acid and the zinc. This useless effect is called *local action*: it can be stopped by using pure zinc, from which impurities have been extracted, which is effective but very expensive, or by keeping the impurities from touching the acid and zinc at the same time. This latter can be done, if we can find a varnish which will cover up the impurities and not the zinc; and *is* done by quicksilver or mercury.

EXPERIMENT 35. Take a strip of commercial zinc; to clean it dip it into dilute sulphuric acid until it begins to give off bubbles of hydrogen, then, without drying it, put a drop or two of mercury on it and spread it over the zinc with your finger. Spread it over the whole of the zinc where it has been cleaned, and shake off any excess of mercury into a dish. As the mercury dissolves zinc, this excess mercury is not pure enough to put back in the stock bottle, and a special dish should be kept for such dirty mercury.

You will find that the mercury sticks to the zinc, giving it a bright surface: this process is called *amalgamating* the zinc. The surface consists of a paste of zinc dissolved in mercury, and the impurities (chiefly iron and arsenic), which are not soluble in mercury, are covered up.

Put this amalgamated zinc into the acid, and note whether any Local Action occurs.

Now put into the same vessel of acid a strip of copper or carbon and let the two strips touch; look out for chemical action, as shown by effervescence from the copper.

By amalgamating commercial zinc you have made it act like pure zinc.

After the zinc in the surface layer of paste has been dissolved by the acid, more zinc is dissolved by the mercury and brought up to the surface, but the impurities float up through the layer of mercury, and although they may for a short time set up a local action by touching the zinc in the surface layer, the hydrogen bubbles so produced tend to float them away from the plate.

Thus the amalgamation protects the zinc for some considerable time, but not indefinitely; after a while the mercury will be found to collect in drops on the surface and must be spread again, or fresh mercury put on.

CHAPTER II

The Voltaic Cell and Simple Galvanometer

46. Simple voltaic cell. In the year 1800 an Italian named Volta was attempting to account for an observation made by another Italian named Galvani; namely, that whenever two different metals touched one another and also the nerve and muscle of the leg of a dead frog the muscle contracted.

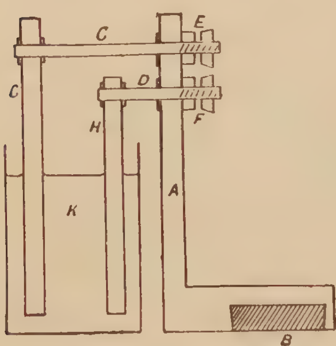


Fig. 38.

He discovered that, if two different metals, such as zinc and copper, are put simultaneously in the same vessel of acid and joined by a wire, 'electricity,' as it had been called by Dr. Gilbert (see p. 192), would flow from one to the other metal. In honour of this discovery such a combination is called a **Voltaic cell.**

It will be convenient to support the zinc and copper or carbon on a firm wooden stand, so that wires can be attached, and the plates dipped into acid when required. A simple and satisfactory form is shown in Fig. 38.

Here *A* is a wooden stand (weighted with lead at *B*) in which are fixed two brass rods, *C* and *D*. Binding screws, *E* and *F*, are attached to these, in which copper wires can be fixed, and to the other ends of the rods are attached plates of zinc and copper or carbon, *G* and *H*. These can be made to stand in acid in a square glass vessel *K*.

The zinc should be 'amalgamated' (see p. 47) by rubbing quicksilver on it, and as it and the acid are the only parts of the cell which get used up, it should be in the form of a thick plate.

Such a combination as this we will call a Simple Cell.

EXPERIMENT 36. **Magnetic effect of an electric current.** Get a pocket-compass mounted in a brass box in which a needle moves over a dial graduated in degrees (one which has a 'floating card' is not suitable), and a block of wood, as in Fig. 39, with a circular pit in the middle, cut to take the compass-box fairly tightly, and with a groove running round the block. Two or three pin points should be stuck in the bottom of the block so that the points just stick out and can be pressed into the table to keep the block from slipping about.

Put the compass-box in the hole in the block and carefully turn it so that the N.-S. line (from which the graduations of degrees start on both sides) is parallel to the groove. Then turn the block round until the needle lies accurately along this line.

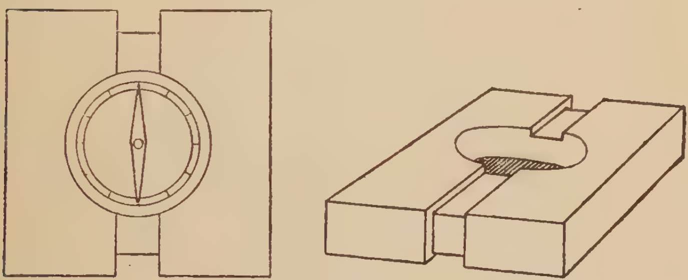


Fig. 39.

Now take a simple cell, and attach the ends of a wire about two metres long to the two binding screws, which will be called the **Poles** of the cell. Lay the wire, with the electric current flowing along it, in the groove above and parallel to the needle, and note whether the north end of the needle turns to E. or W., and the number of degrees it is deflected when it comes to rest. Gently tap the block to avoid friction at the support of the needle.

Keeping everything else unchanged, uncouple the two ends of the wire and interchange them, screwing them up again to the opposite poles, and note the effect on the needle.

47. This experiment will demonstrate the fact that an electric current has a definite direction of 'flow' in a wire; we are able to reverse the effect it produces by interchanging the ends of the wire.

We do not know with certainty that anything actually flows along the wire, but all the language that has grown up round the subject goes on the assumption of such a flow, and it is very probable that *electrons* (see pp. 169, 201) do flow along the wire.

We may assume that the current flows from the zinc to the copper plate along the wire, or the other way, as we please; we have as yet seen nothing to suggest which is the true direction of flow. It is always taken as flowing along the wire from the copper or carbon *to the zinc.*

The copper pole is called the Positive Pole and the zinc the Negative.

Experiment 37. Arrange the wire in the groove *above* the needle, as in Experiment 36, and attach it to a simple cell in such a way that a current runs from south to north. Note the direction and amount of the deflection of the N. pole of the needle.

Next put the wire instead in the groove *below* the needle, and note the direction and amount of the deflection.

You can in this way fill up the gaps in the following table, which you should enter in your note-book.

A current from N. to S. above a needle sends the N. pole to the ...
A current from S. to N. above a needle sends the S. pole to the ...
A current from N. to S. below a needle sends the N. pole to the ...
A current from S. to N. below a needle sends the S. pole to the ...

48. Corkscrew rule. Although such a table covers all that you have found out it is not a convenient one, as it would be difficult to remember. The whole table is contained in what may be called the Corkscrew Rule, which is shorter and still more comprehensive. It was suggested by Clerk Maxwell *.

Imagine that a corkscrew lies along the wire in which the current flows, and that it is twisted round so that it would go into, or come out of, a cork in the direction that the current is flowing. Then a N. pole would be urged by the current in a circle round the wire in the same direction as the handle of the corkscrew actually moves round it. Of course a S. pole would be urged to move in a circle round the wire in the opposite direction.

This can be expressed briefly as follows: *The motion of a current and of a N. pole round it are related in the same way as the translation* †

* Cavendish Professor of Physics at Cambridge until 1879.
† i. e. the 'forward or backward travel when the screw is turned in a cork.'

and rotation of a corkscrew. Or, *A N. pole is urged to move round a current in the same way as the handle of a corkscrew which is being turned so as to move with the current.* You should apply the rule to the cases in the table of results which you have observed, and see if it is borne out by them.

There are several other forms of the rule which have been found to commend themselves to people who have to use it frequently in practice.

The form called 'Ampère's Rule' is—'Imagine a man swimming along inside the wire with his head in the direction in which the current flows, and let him face the needle. Then the N. pole will be driven towards his *left*.'

Professor Fleming suggested the following: 'Clench your right hand and open the thumb and first two fingers, so that all three are at right angles to one another. Place them so that the first finger points along the wire in the direction in which the current is flowing, and so that the second finger points to the needle, then the thumb points in the direction in which the N. pole of the needle is driven.' This is a good deal used by engineers; Ampère's rule, though convenient, should not be adopted, as it is liable to be confused with another 'Ampère's rule' to be given later (p. 143).

49. To increase the magnetic effect of a current. Since currents running one way above a needle and in the opposite direction under the needle tend to turn the needle the same way, if both act simultaneously it is reasonable to suppose that the effect will be greater than when either acts alone.

This experiment should be tried.

Experiment 38. Set the block and compass as in Experiment 36, and hold the wire, carrying the current from a simple cell, in the groove above the needle—note the deflection.

Now pass the wire back under the block so that it makes one complete turn round the compass, and note the deflection when the current runs.

Coil the wire round the block five or six times, and again take the reading of the N. end of the needle.

Remember always to wait till the needle comes to rest, and to tap the block gently.

50. If you apply the corkscrew rule separately to the various

parts of the wire, *A*, *B*, *C*, *D*, *E*, in the diagram (Fig. 40) (in which the current is supposed to run as shown by the arrow), you will find that each part of the current tends to urge the N. pole *out* of the paper; so that the effect of one complete turn ought to be more than twice as great as that produced by the current passing once over the needle; and if the wire is coiled round and round the needle each complete turn should add its own effect.

You will notice, however, that the angles, through which the needle is deflected as the number of turns is increased, do not increase in proportion to the number of turns. This is because the force of the current on the poles of the needle is in a constant direction, and is not at right angles to the needle when it is deflected, so that as the deflection increases the deflecting force acts at less advantage, and at the same time the restorative force acting on the needle, which tends to keep it in the magnetic meridian, acts to greater advantage. Thus an infinitely large force produced by a current in the wire would be needed to keep the needle at right angles to the wire: just as the wire top of a tennis-net sags somewhat even when tightly strained, and an infinitely large tension would be required to pull it up to a straight line.

Fig. 40.

51. Simple galvanometer. An instrument consisting of such a block and compass as was used in the last three experiments, with a wire coiled round the groove several times, is called a Galvanometer. The wire must be 'insulated,' i.e. wrapped with silk or cotton or covered with india-rubber, to keep apart the metal in adjacent turns of the wire, otherwise the current would flow directly from one turn to the next, and not pass round the coil. The ends of the wire are usually fixed to two binding screws on the block, to which wires from the cell can be attached.

Before the galvanometer is used it must be turned so that the coil lies in the plane of the magnetic meridian: the needle will then be parallel to the wire in the coil.

Such an instrument is of use:—

(1) To show the existence of an electric current.

(2) To show the direction of the current.

(3) To compare the strength of different currents.

According to the uses for which it is designed a galvanometer is wound either with a comparatively small number of turns of fairly thick wire, or a very large number of turns of thin wire. Wire is made of different thicknesses, and its thickness is generally expressed by referring it to the standard gauge (S. G.) (see Appendix B); a number implies a certain diameter of wire, the smaller the number the thicker the wire. For most purposes in a laboratory, for conveying a current from one instrument to another, wire between No. 18 and No. 22 (S. G.) is most convenient: No. 28 is fairly thin, No. 36 decidedly so, and No. 40 as thin as a hair. It can be ordinarily bought covered with silk as thin as No. 46, while it is troublesome to bend if it is thicker than No. 12.

The most convenient simple galvanometer is one wound with about ten turns of insulated copper wire about No. 22.

Unless these galvanometers are most carefully wound, it will be found that the needle will be deflected a different number of degrees by the same current if its direction of flow round the coil be reversed: hence, as the galvanometer is only to be used for comparing one current with another, it is well to mark one of the binding screws with a + to signify that the current should always enter the galvanometer there, and to be careful always to use the N. end of the needle in observing the deflection.

52. To set up a simple galvanometer. The following is a summary of what has been said above as to the precautions necessary in using even this simplest kind of galvanometer.

1. See that the N.-S. line of the compass-box is parallel to the wires of the coil.

2. Turn the block until the compass-needle points to the 0 of the scale (i. e. lies along the N.-S. line or is parallel to the coil), the N. end of needle being over the N. point in the compass-box.

3. Attach the wires so that the current enters the galvanometer by the binding screw marked +.

4. Tap the block gently before taking a reading.

5. Read the deflection of the N. end of the needle.

If these precautions are taken, the angle observed will give you a measure of the current flowing; although it will not be proportional to the current, yet you can compare currents one with another by its means.

CHAPTER III

POLARIZATION

53. The most familiar use of a voltaic cell is in ringing an electric bell. We will defer explaining how it does so till Chapter XI, but will now make some experiments with it in order to see how a cell behaves when in use.

EXPERIMENT 39. Get a simple cell of copper and amalgamated zinc; dry the copper plate, and immerse both in dilute sulphuric acid, not stronger than 1 part in 40 of water. Connect the terminals of a bell to the poles of the cell by means of two pieces of copper wire; note how loudly it rings. Keep it ringing for 3 or 4 minutes (to decrease the noise put your finger on the bell), and observe whether it continues to ring with the same vigour.

You will probably find that the current furnished by a simple cell falls off to a certain extent as the cell is used, but that it reaches a steady state after a time and will maintain that state as long as the acid is not seriously weakened by use. We must now investigate the cause of this falling off.

EXPERIMENT 40. Take a simple cell that has been used to furnish a current for some little time as in Experiment 39, and find how strongly the bell is rung. While the bell is still connected to the cell, rub the bubbles of hydrogen from the copper plate with your finger (or a glass rod, or a wooden match) and note whether the current recovers to any extent its former strength. If not, take out the plates, dry the copper with a piece of blotting-paper, replace in the acid, and note whether the cell has recovered its strength.

You should now have proved that this decrease in the current is due to a collection of hydrogen occurring on the positive plate.

A cell in which gas has collected in this manner is said to be *Polarized.*

The loss of constancy of the current detracts from the value of the cell to such an extent that a simple cell is never used in practice.

The layer of gas does harm in two ways, of which the only one obvious from the preceding experiment is its preventing the liquid from getting access to the copper.

The other and equally important effect will be dealt with later (p. 170).

A great amount of ingenuity has been expended in overcoming the polarization, and numbers of cells have been invented in which the result has been practically accomplished, at the expense in many cases of introducing complication in working or considerable cost of materials.

However, so long as a voltaic cell was the only available source of an electric current, every improvement was very valuable: but now that large supplies of electric energy can be furnished cheaply and steadily by a dynamo driven by a steam engine, the majority of forms of cell possess only an antiquarian interest. We can therefore confine our attention to two or three types which are still largely used, and which possess features of theoretical interest.

54. To remove the polarization of a cell. There are three principal methods of destroying polarization, which we may class as:—

1. Mechanical.
2. Chemical.
3. Electro-chemical.

1. **Mechanical.** This is now never employed. Experiment 40 illustrated one method, fairly effective but troublesome.

Smee invented a cell in which the copper was replaced by a sheet of silver covered with a rough layer of finely divided platinum: the bubbles of hydrogen rise much more freely from such a surface than from the smooth copper, but even in this cell the current rapidly decreases in use.

Now that hard carbon is to be obtained cheaply, plates of this material can be used instead of platinized silver, and are in many ways an improvement on it.

If the surface of the plate is very large, and the cell is only required to furnish current at intervals, allowing fairly long periods of repose during which the hydrogen has time to disappear, this form of cell gives satisfactory results. It is adopted in the Law Battery, largely used for electric bells in the United States. In this case the exciting liquid is a solution of sal ammoniac, not sulphuric acid.

2. **Chemical.** This method consists in adding to the 'exciting liquid' used (such as sulphuric acid) some strongly oxidizing substance which will destroy the hydrogen as fast as it is formed, thus doing away with the whole trouble.

Chromic acid (or bichromate of potash with sulphuric acid) is the agent most frequently used to effect this.

3. **Electro-chemical.** In this process 'double fluid' cells are employed, by which the electric current in the cell itself promotes chemical changes, resulting either (i) in the deposition on the positive plate of a layer of metal instead of hydrogen *, or (ii) in the production there of a gas which is soluble in the acid.

EXPERIMENT 41. **Chemical depolarization.** Take a simple cell of carbon and amalgamated zinc in dilute sulphuric acid (1 in 40): connect it up to an electric bell, and observe how strongly it rings.

Connect the poles by a piece of copper wire (this is called *short circuiting* the cell, and is very destructive to most cells) for a minute, and again observe how it rings.

See whether rubbing the carbon plate removes the polarization.

Compare the current and the polarization with that obtained (in Experiment 39) for a copper and zinc cell.

Now add to the acid a teaspoonful of chromic acid †.

Test the current furnished by the cell containing this chromic acid, and the amount of polarization caused by short-circuiting the cell.

While the cell is short-circuited examine the positive plate for bubbles of hydrogen.

If you have added enough chromic acid these will be nearly all

* By this means the positive plate is merely thickened as the current flows, and the liquid has perfect access to it; the other effect mentioned above is also avoided.

† Chromic acid is sold commercially in the form of a red pasty powder, which really consists of chromic anhydride (which becomes chromic acid on

destroyed; but probably bubbles will still be formed on the zinc plate.

Do not leave the plates standing in the acid except while an experiment is actually in progress, as amalgamation does not protect zinc from the action of chromic acid.

The effect of adding chromic acid to the sulphuric acid is to increase the initial current furnished by the cell, and to maintain the increased current in use: its disadvantage is that it is a very strong acid which cannot be left in contact with zinc.

Carbon is always used with chromic acid, in spite of the difficulty of making a satisfactory joint between the carbon and the wire used to carry away the current: this can be done easily by means of a binding screw for a short time, but in order to make a permanent electrical connection it is necessary to cast a metal cap of lead and antimony on the top of the carbon plate and to fix the binding screw in this.

CHAPTER IV

Voltaic Cells

55. The following description of some types of cell in common use in a laboratory need not be read at this point of the course, which can be carried on with the simple chromic acid cell above described until need arises for a more complicated one, when its construction may be referred to. Otherwise each cell in succession

the addition of water), together with sulphuric acid to the extent of about one quarter of the whole weight. This acid is left in from the process of manufacture, and is useful rather than otherwise when employed in a cell. When it is removed the chromic anhydride is much more expensive.

If chromic acid cannot be got, potassium bichromate can be added instead, but it is not so good, as it uses up some of the sulphuric acid in producing chromic acid, and after the cell has been in action for some time chrome alum crystallizes out on the plates and is troublesome to remove: with chromic acid no such solid residue is formed.

may be examined and set up in the laboratory according to this explanation.

56. Bottle bichromate cells. The simple chromic acid cell has long been adapted for use by arranging it so that the zinc plate is easily movable out of the acid: the carbon plate can be kept immersed without damage.

To prevent evaporation the whole cell is closed and forms a kind of bottle in which the acids stand permanently to such a depth that the zinc can be lifted clear of the liquid.

Two plates of carbon are generally used, one on each side of the zinc and connected together at the top; this provides a greater surface over which the hydrogen can be attacked by the chromic acid.

Fig. 41. Bottle bichromate cell.

The carbon and zinc plates are made to stand close together in order to keep down the internal resistance (see p. 68).

The proportions by weight usually employed are, if bichromate of potash is used, 100 parts water, 15 parts bichromate of potash, 30 parts sulphuric acid.

If chromic acid is used, 100 parts water, 15 parts *commercial* chromic acid, 8 parts sulphuric acid forms a suitable mixture.

When the chromic acid has become spent, it turns green (owing to the formation of chromic sulphate), so that it is always easy to tell when it requires renewal.

This is a useful form of cell, being ready for use whenever required and capable of furnishing a large current of electricity.

It has, however, one disadvantage, that when the zinc is lowered into the acid for use, it is attacked by the chromic acid. When current is drawn from the cell, the zinc must be dissolved by the sulphuric acid to an extent depending on the current, but this action by the chromic acid is wasteful, since it is 'local.'

To avoid this a somewhat more complicated form is commonly used, called a *double fluid cell.*

57. Double fluid chromic acid cell. In a chromic acid cell the chromic acid is needed at the surface of the carbon; it only does

harm at the surface of the zinc. In a double fluid cell the chromic acid is kept away from the zinc by means of a **porous pot**, which separates the carbon and zinc. This consists of a jar of unglazed earthenware (*A*, Fig. 42)—it is full of very minute pores or holes, through which liquids can diffuse very slowly*. When it is used to separate two liquids it contains enough liquid in its pores to furnish a passage to an electric current, so that the metal plates on each side of it act as if dipped in the same vessel; but the process of mixing of the two liquids goes on so slowly that but little passes through even in a day.

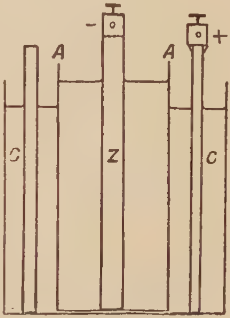


Fig. 42.

In the present case the amalgamated zinc and dilute sulphuric acid are put in the porous jar; this is immersed in an outer jar containing the carbon plate and a mixture of sulphuric and chromic acids (or bichromate of potash).

In this form the cell may be used to produce a steady current for many hours; no noxious gases are given off, and the current is furnished at a fairly cheap rate. Three or four such cells will steadily light a small glow-lamp, or can be economically used for charging small accumulators, e.g. those used with ignition coils for motors.

58. Electro-chemical depolarization. Bunsen's cell. This form of cell differs only from the double fluid chromic acid cell in the substitution of concentrated nitric acid for the mixed chromic and sulphuric acids round the carbon.

Any strong oxidizing agent can be used instead of the chromic acid to destroy the hydrogen, as carbon is practically unaffected by any of them: and nitric acid is one of the cheapest and most effective of such agents.

* When not in use porous pots should not be allowed to dry, but should be kept entirely immersed in water. This keeps them clean, prevents the enclosed salts from crystallizing on their surface and so destroying it, and keeps them ready for use, as the cell will not work until the pot is soaked.

Before a porous pot is taken into use it is worth while to dip it mouth downward for an inch into melted paraffin: this keeps the salts in the solution from creeping up to the top edge of the pot, crystallizing there, and so breaking off the top of the porous pot.

The great objection to its use is that in the process of oxidation the nitric acid is itself broken up, and gives forth nitrogen peroxide, a red gas that is poisonous, and destructive of all kinds of brass work on instruments. Hence such a cell is never used inside a laboratory—it must be kept in a fume closet or on a shelf outside a window. The carbon with its surrounding nitric acid is usually put inside the porous pot, the zinc and sulphuric acid being in the outer pot.

An important difference will be noticed between this and the double fluid chromic cell - in the latter there is sulphuric acid on each side of the porous pot, so that it is continuous from one plate to the other, the chromic acid being added where it is required to effect the depolarization. In the Bunsen cell we have an instance of the third class of cell, that in which the depolarization is produced by electro-chemical means, for we do not have both plates dipping into the same fluid.

59. We have not as yet in these experiments come across any evidence that the electric current, which flows from the carbon to the zinc plate along a wire, actually completes the circuit by flowing through the liquid into which these plates dip; but it can be shown to do so *.

We must assume that the hydrogen which is liberated from the sulphuric acid at the surface of the zinc travels in some way with the current until it appears on the surface of the carbon plate.

If in process of passing through the cell the current has to leave sulphuric acid and pass through nitric acid, it is quite reasonable to suppose that the hydrogen travelling with the current attacks the nitric acid on meeting it, and that the products of this chemical change are transferred with the current to the surface of the carbon plate. Being very soluble in nitric acid they do not appear as gases or produce polarization.

The passage of an electric current through liquids, and the chemical changes thereby produced will be dealt with in Chapter XIV on Electrolysis.

60. Grove's cell. Before gas carbon was easily procurable Sir William Grove had devised a cell which contained a thin sheet of *platinum* dipping in concentrated nitric acid in a porous pot,

* This can easily be tried by magnetizing a sewing-needle and floating it on the surface of the acid between the plates of a simple cell, which must be sufficiently far apart to allow it. On joining the poles the needle will move in a way that indicates a current flowing *from the zinc to the carbon*.

which was immersed in an outer jar containing sulphuric acid and zinc. Bunsen's cell was merely a modification of the Grove's cell to avoid the high cost of the platinum, a metal nearly as expensive as gold.

Grove's cells are so arranged that there is only a thin layer of liquid between the platinum and zinc plates, and are usually made up in rectangular jars (as in Fig. 43, which shows two Grove's cells connected together), the zinc being bent over so as to be attached easily to the platinum plate of another cell.

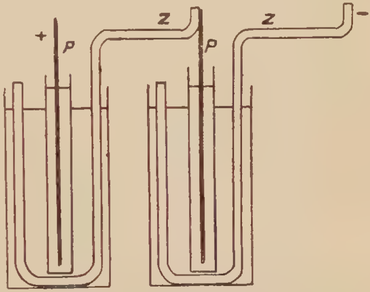


Fig. 43. Two Grove's cells.

61. Daniell's cell. If a constant current is required, which need not be a very large one, a Daniell's cell may be used. This cell consists of a rod or plate of zinc in dilute sulphuric acid, separated by a porous pot from a concentrated solution of copper sulphate containing the copper plate. The copper is sometimes made into a complete vessel and acts as the outer jar, but this is only an expensive laboratory form.

Of course the porous pot can contain either the copper and copper sulphate solution, or the zinc and acid; it is better to adopt the latter arrangement as then the surface of the copper is large.

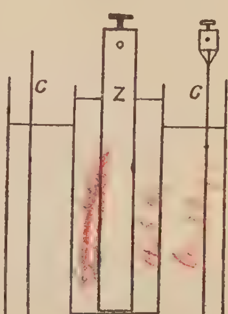


Fig. 44.

The action that goes on when the cell produces a current is as follows:—

The sulphuric acid dissolves some zinc, forming zinc sulphate as usual, and hydrogen is liberated and travels with the current in the liquid towards the copper plate. On passing through the porous pot and meeting the copper sulphate solution, the hydrogen displaces copper from the copper sulphate and takes its place (forming sulphuric acid), and the copper passes on with the current and is deposited on the copper plate. As the copper plate is merely thickened by this deposited layer there is no polarization.

It will be seen that the copper sulphate gets used up, and if the cell is required to work for a long time provision is made for a supply of crystals of copper sulphate, so placed that they may be dissolved as they are needed.

In this case the zinc plate is made thick, and no effort is made to renew the sulphuric acid, because it is found that the cell will work (though not so strongly) if charged originally with zinc sulphate solution instead of sulphuric acid. Zinc then passes through the porous pot instead of hydrogen, and there is no change in the liquid surrounding the zinc plate, but zinc sulphate is formed in the liquid round the copper plate.

This form of the cell is the more constant, as the gradual weakening of the sulphuric acid in the ordinary form results in a gradual loss of strength.

62. Gravity Daniell cell. For cells where a porous pot is undesirable it can be dispensed with by making use of the high specific gravity of copper sulphate solution. The copper plate is placed at the bottom of a pot, covered with copper sulphate solution, and the zinc plate is suspended at the top, immersed in weak sulphuric acid which floats on the copper sulphate. The liquids will slowly diffuse into one another, but not at a great rate if the cell is not disturbed and if a current is taken from it fairly steadily: for instance they are used for telegraph lines. Such a cell can be made very cheaply and easily as follows.

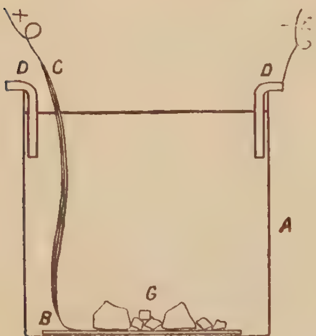


Fig. 45.

Get a jam jar (A) and cut a piece of thin sheet copper (B) to lie easily on the bottom. Solder to this (see p. 295) a piece of rubber-covered copper wire (C) about a foot long, or a piece of cotton-covered wire, which you must coat with rubber solution (from a tyre-repairing outfit) and wrap round with tape, afterwards well coating this too with the solution.

A piece of sheet zinc (D) must be cut about two or three inches wide, and long enough to go nearly round the jar, and must be bent

round into a cylinder (heat it to make it bend easily), and two or three 'ears' must be cut and bent outwards to keep the cylinder from slipping down into the jar.

Solder a piece of copper wire (*E*) to one of the ears, and amalgamate the zinc. Now put a handful of crystals of copper sulphate (*G*) on the top of the sheet copper, fill up the jar with dilute sulphuric acid, and leave it until some of the copper sulphate has dissolved.

In the Indian Telegraph Service where these cells are used, the zinc is taken out and washed, and the scum taken from the water, every day.

63. Leclanché cell. The cells hitherto described have been devised to secure constancy of current or large output. They have mostly involved some trouble in preparing them for use and cleaning them after use.

For many purposes only a moderate current is needed occasionally, and its constancy is not an important point, while it is most important that the cell should never need attention; as, for example, for the ringing of electric bells or the working of a telephone. Some form of Leclanché cell is universally used for such a purpose.

In this cell the plates are as before, carbon and zinc, but the exciting liquid is, instead of acid, a solution of sal ammoniac (ammonium chloride).

EXPERIMENT 42. Test the current produced by a simple cell of carbon and zinc immersed in a solution of ammonium chloride, connected to an electric bell.

Short-circuit the cell and test the polarization produced.

Leave the cell to rest for five minutes with the wires disconnected, and again test whether the cell has recovered its strength.

The affinity of ammonium chloride for zinc is so small that no local action occurs even if the zinc is not amalgamated, so that the zinc can be left indefinitely in the liquid without damage.

Depolarization is effected in the Leclanché cell by surrounding the carbon plate with lumps of manganese dioxide; which is an oxidizing agent, but does not, as it is not a liquid, destroy the hydrogen as fast as it is formed. The cell polarizes when a current is taken out, but on being allowed to rest, the hydrogen is slowly destroyed by the manganese dioxide.

In order to make the surface of contact between carbon and manganese dioxide as large as possible, the carbon plate is generally put

in a porous pot or sack full of broken coke * and manganese dioxide. (In the diagram this is indicated only at the bottom.)

The ammonium chloride solution thus reaches both zinc and carbon.

In the Carsak cell the zinc instead of being in the form of a rod is a cylinder surrounding the porous pot containing the carbon. This lessens the resistance of the cell.

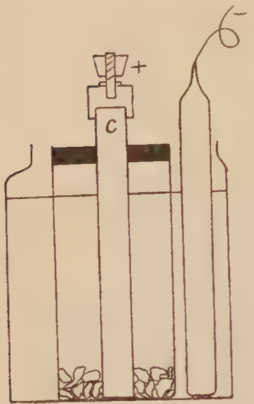


Fig. 46.

Instead of the porous pot to contain the depolarizer, sometimes the coke and manganese dioxide are compressed together into blocks which are attached to the carbon plates, and the whole immersed in the sal ammoniac solution. This form is called the *agglomerate block Leclanché*.

EXPERIMENT 43. Get an agglomerate block Leclanché cell containing very little liquid; connect it to an electric bell.

Short-circuit the cell for a minute and test the polarization: if none is produced short-circuit again.

Let the cell rest for five or six minutes, and see whether it has become depolarized.

The chemical action which goes on when the cell is at work is somewhat more complex than in a simple cell. The zinc is dissolved in the ammonium chloride, and forms a double chloride of zinc and ammonium (which is often found crystallized out on the zinc rod of a cell that has been long in use) and hydrogen and ammonia are formed.

The hydrogen, if in small quantities, disappears into the pores of the carbon, and is afterwards oxidized by the manganese dioxide (forming water), and the ammonia dissolves in the liquid, and slowly diffuses into the air.

The only thing that requires to be replaced in a Leclanché cell that has ceased to ring its bell is the ammonium chloride or water. The final failure is generally due to the whole of the manganese dioxide being used up.

64. Dry cells. In order to make Leclanché cells more portable and less liable to evaporation they are often arranged as 'dry cells.' The zinc and carbon (the latter packed round with coke and manganese

* Coke is a cheap and impure form of carbon.

dioxide, usually enclosed in a piece of sacking instead of a porous pot) are closely surrounded with a mixture of plaster of paris and solid ammonium chloride, just damped with water.

The whole cell can now be sealed up, a small hole being left through which any evolved gas may escape, as otherwise the cell may burst. As such gas cannot readily escape a dry cell should never be short-circuited. If a dry cell fails, the introduction of a little water through the hole above described may restore its vigour, but probably will not do so.

65. Storage cells or accumulators. These are not 'primary' cells and will not be fully dealt with here *, but are mentioned because they are often used in practical work, as they furnish large and steady currents. They consist of two lead plates in sulphuric acid : one of the plates is partially transformed into lead peroxide by passing an electric current through the cell. (This electric current has to be produced by means of some cells such as we have discussed, or by a dynamo.) So long as the plates differ the accumulator acts as a voltaic cell and will furnish a current. When it is 'run down,' the passage of a current through it again will reduce one of the plates to lead, and oxidize the other to lead peroxide, and the accumulator will once more act as a voltaic cell.

The most essential point to be remembered in their use is, *never short-circuit an accumulator even for a moment*; such a large current would flow that the cell would be ruined.

66. Standard cells. The only other cell with which we shall be concerned is the *Standard Cell*, which is never used for furnishing a current of any magnitude.

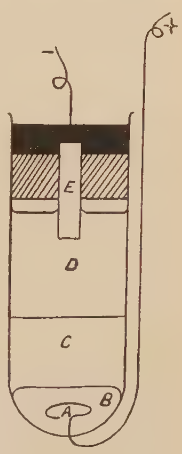


Fig. 47.
Clark's Cell.

The Latimer Clark's cell consists of a rod of pure zinc (E) dipping in a concentrated solution of zinc sulphate (D). This lies on, and percolates down into, a layer of powdered mercurous sulphate, which is insoluble; this again lies on a layer of mercury which is the $+^{ve}$ pole of the cell. It is connected to the outer binding screw by a platinum wire which is sealed into the bottom of the tube.

The powdered mercurous sulphate is made into a thin soup with zinc sulphate solution ; when the current flows zinc is dissolved from E, some of the solid mercurous sulphate becomes zinc sulphate, and hands on its mercury to B.

* See Chapter XIV.

The *Weston Standard Cell* differs in construction from the Clark's cell in the use of cadmium in place of zinc.

To sum up the points of the various cells dealt with :—

	Metals.	*Exciting Fluid.*	*Depolarizer.*	*E.M.F. in volts* (see p. 99).	*Use, &c.*
Bottle bichromate	Zinc and carbon	Sulphuric acid	Chromic acid	2·1	Experiments where large currents are needed for a short time. Wasteful.
Double fluid chromic	" "	" "	" "	2·1	Experiments where large currents are needed for a short time. No fumes.
Bunsen's . .	" "	" "	Nitric acid	1·9	Fumes. Cheap.
Grove's . . .	Zinc and platinum	" "	" "	1·94	Fumes. Expensive in first cost.
Daniell's . .	Zinc and copper	" "	Copper sulphate	1·11	Small but constant current. Cheap.
Leclanche . .	Zinc and carbon	Ammonium chloride	Manganese dioxide	1·41	Intermittent work. No attention needed.
Storage cell .	Lead and lead peroxide	Sulphuric acid		1·9–2·0	Large steady currents. Needs charging.
Clark standard	Zinc and mercury	Zinc sulphate	Mercurous sulphate	1·434	Standard of E.M.F
Weston standard.	Cadmium and mercury	Cadmium sulphate	" "	1·0183	" "

CHAPTER V

Resistance

Experiment 44. Get a simple chromic acid cell and a simple galvanometer wound with about ten turns of copper wire.

You will need pieces of thick and thin platinoid * wire : a metre of No. 22 and No. 30 will be convenient ; also ordinary copper connecting wire. Couple the galvanometer to the cell by two copper wires and note the deflection.

* Platinoid is composed of copper 60 parts, zinc 25 parts, nickel 14 parts, and tungsten 1 part.

Substitute for one of the copper wires a metre of No. 22 platinoid; substitute for this a metre of No. 30, then half a metre of No. 30; in each case note the deflection of the galvanometer.

Do not waste time or the strength of the cell may alter. If you think this has altered, work through the tests of the various wires in the reverse order and take the 'mean' or 'average' value of the deflection in each case. This is not strictly accurate, but sufficiently so for our present purpose, since we only wish to get the currents in their order of magnitude.

Tabulate your results.

67. You will observe that the same cell is capable of sending a greater current through some wires than through others; this is expressed by saying that some wires have less **resistance** than others, or that they have a greater **conductance.**

The former point of view is more often adopted, though the latter is convenient in some cases and is the more reasonable, since the conducting power, not the resisting power, is usually the valuable property of a wire.

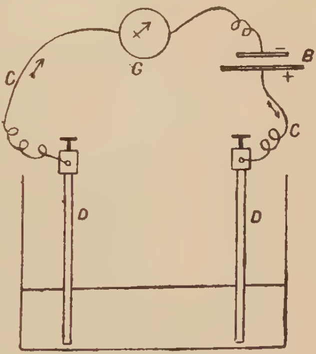


Fig. 48*.

Your experiment ought to prove to you that a *thin* wire has more resistance than a *thick* one, a *long* one than a *short* one, and *platinoid* more than *copper*.

Every metal possesses its own power of conducting electricity, silver being the best conductor; and such substances as china, wood, glass, and ebonite offer such an enormous resistance to the flow of current that they are called **non-conductors** or **insulators.**

Experiment 45. **To test whether liquids offer resistance to the flow of an electric current.** Substitute for one of the

* Fig. 48 shows how such an arrangement of apparatus is usually represented.

G is a conventional sign for some sort of galvanometer, *C* for connecting wires, and *B* for a cell.

The longer line is usually taken to represent the positive plate. To prevent mistake, it is well to put a + by it, or to put arrows by the connecting wires to show the direction in which the current should flow.

platinoid wires in Experiment 44 a glass vessel containing a weak solution of zinc sulphate. Into this dip two plates of zinc attached to two copper wires, one connected to the galvanometer, the other to the chromic acid cell. In this way the current has to flow through the liquid.

Now vary the distance between the two plates *D* and observe the deflections of the galvanometer: this is equivalent to changing the length of a wire conductor. Then vary the amount of zinc sulphate solution in the jar, starting with very little and gradually filling up. This is equivalent to gradually thickening a wire.

Compare the behaviour of a liquid with that of a solid in this matter.

Such an arrangement of zinc plates dipping in zinc sulphate is often of use when we have to vary the resistance opposing the flow of a current round a circuit; it is called a Rheostat (see p. 290).

68. Since the current flows through the cell, and liquids offer resistance (and this resistance is enormously greater than that offered by a metal wire of the same length and cross-section), if we want a large current the length of liquid traversed must be as small, and the cross-section as large, as possible.

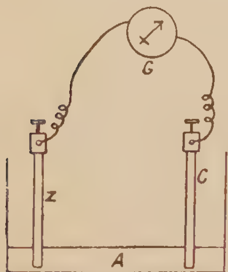


Fig. 49.

EXPERIMENT 46. **To investigate the 'internal resistance' of a cell.** Take a simple galvanometer, wound with a few turns of copper wire, and a vessel, as in Experiment 45, which is to contain very dilute sulphuric acid.

Take plates of zinc (*Z*, Fig. 49) and copper (*C*) or carbon, as in Experiment 45, connected up to the galvanometer (*G*).

Put these plates, one at each end of the vessel, and pour in a shallow layer of dilute acid (*A*).

Note the deflection and pour in more acid; observe if the current increases.

Now, keeping the same depth of liquid, bring the two plates closer together, so as to reduce the distance which the current has to travel in the liquid, and again note the deflection.

Hence the plates in a cell should be as large and as near together

as is convenient; but they cannot be put very close together as the liquid between them would soon get exhausted when the current passed.

69. Standards of resistance. We have roughly compared the resistance offered by various pieces of wire, and of various quantities of liquid, to the electric current: but before numerical measurements of such resistances can be made, a standard or unit of resistance must be agreed upon, and determined by law; if possible by international law.

The first experimenters took a piece of wire which they had in their laboratory, and which they found to offer a convenient amount of resistance, to serve as a unit with which to compare the resistance offered by any other conductor.

Thus Jacobi fixed on a piece of copper wire, and made copies having the same electrical resistance, which he sent to his friends, so that their results might be expressed in terms of this standard. This was called Jacobi's Standard.

Dr. Siemens suggested using a column of mercury of definite length and cross-section: this was preferable to defining the standard as a wire of definite metal, length, and cross-section, since the resistance of a wire depends on its age and previous history (e.g. how it was drawn and annealed), while mercury can be obtained pure, and has no such history.

The British Association, in 1861, appointed a committee to settle the best unit. They recommended that the unit should be defined according to a theoretical method, and that pieces of wire having this resistance should be made for sale.

These were generally adopted, and the name of **ohm** was given to the unit in honour of Dr. G. S. Ohm, Professor of Physics in Munich (1849-54).

70. This standard has since been modified at international conventions in 1884 and 1908, and an 'ohm' now means the resistance of a 'column of mercury at the temperature of melting ice, 14·4521 grammes in mass, of a constant cross-sectional area, and of a length

of 106·300 centimetres,' which was the practical standard adopted by the international convention of 1908.

Standard 1-ohm coils can be bought, consisting of a wire having this resistance.

71. Multiples and submultiples of the ohm. Multiples of the unit are made by taking longer or thinner wires, so as to have a resistance some definite number of times that of the standard: just as 2, 4, 7, 28 lb. weights are made for convenience instead of having a very large number of single 1 lb. weights.

Thus it is usual to have single coils of 1, 2, 5, 10 ohms of platinoid wire insulated with silk and wound on a reel. Their ends are soldered to binding screws or to thick copper straps or rods, according to the measuring apparatus for which they are designed.

Accurate coils are generally encased in solid paraffin wax which ensures perfect insulation of the wires.

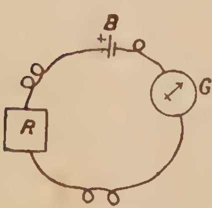


Fig. 50.

EXPERIMENT 47. **To make a copy of a 5-ohm coil.** Take any cell (B, Fig. 50) capable of giving a constant current, such as a chromic acid cell, and a simple galvanometer (G) of low resistance (one wound with a few turns of copper wire).

Connect up 'in series' (i.e. so that the current runs through each in succession) the cell and galvanometer and a 5-ohm coil (R).

Note the deflection of the galvanometer.

Next remove the 5-ohm coil and substitute for it about a metre of No. 30 platinoid wire, and observe the deflection.

If this is less than before, the resistance in the circuit is greater than it was, and the piece of platinoid wire must be shortened until the deflection is the same as before. (It need not be cut, but the part between the binding screws on cell and galvanometer must be shortened.)

The resistance of the platinoid wire is now 5 ohms.

Since the battery may have changed its strength during the experiment, test it again with the 5-ohm coil. If the deflection

is different you must of course readjust the length of the platinoid wire.

When you are satisfied that you can substitute the platinoid wire for the 5-ohm coil without affecting the current, mark the ends of the wire (i.e. the effective ends, where the wire touches the binding screws), measure its length and record it for future use.

Make the wire into a *rough* 5-ohm coil, as described in Appendix D; owing to the lack of sensitiveness in the galvanometer it is probably very inaccurate, but better methods will be explained later by which the error of the coil so made can be accurately measured (see p. 122).

72. Resistance-boxes. If we wish to introduce into a circuit a resistance of several ohms, and have several copies of the standard ohm, it seems reasonable to assume that we shall attain our end by introducing the required number of ohm coils in such a way that the whole current flows through each in succession.

In other words, we assume that a wire twice as long as an otherwise exactly similar wire has twice as great a resistance, and so on.

Remember that we have not proved this yet: it can be proved experimentally, but the method is based on a law called Ohm's Law to be discussed later.

As we are beginning our definitions of resistance, current, &c., by defining the ohm, we might *define* '2 ohms' as the resistance of two single ohm coils in series, and so for all multiples and submultiples. We will, however, follow the ordinary course by assuming for the present that it is true and can be proved on the basis of Ohm's Law.

To have a multitude of single ohm coils to connect up in series when a large resistance, say of 132 ohms is required, would be very inconvenient; hence sets of multiples and submultiples are kept, by which any resistance can be built up (cf. a box of weights).

Such coils would often need connecting together, and the resistance of the connecting wires would introduce errors. The sets of coils are usually arranged in boxes in such a manner that a current may pass through the box from one binding screw to the other, and may be connected through any combination of the coils in series by removing plugs.

The plug resistance-box will now be described: the actual box should be compared with the description.

73. Plug resistance-box. On the top of a box of some non-conducting material such as ebonite are a number of solid blocks of brass (*A*) (see Fig. 51) set in lines and separated by a small distance from the next on either side. These gaps can be bridged by thrusting solid brass plugs (*C*) usually having ebonite handles (*B*), into a suitably shaped hole, cut partly out of each block, so that when the plug is in its place there is good electrical connection between the two blocks. Thus when all the plugs are firmly in their places there is practically no resistance to the flow of current from one binding screw to the other, since there is a continuous rod of metal of large cross-section.

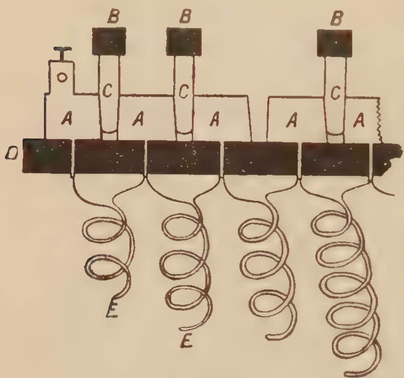


Fig. 51. Resistance-box.

The gaps are also bridged with wires (*E*) of various resistances (multiples and submultiples of the ohm), which are arranged inside the box, connection being made with the blocks on the top by thick wires leading through the ebonite.

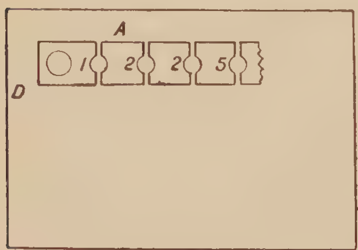


Fig. 52.

When a plug is removed from a gap, the current has to flow through the coil bridging that gap; so that removing a plug has the effect of introducing a known resistance into the circuit *.

Thus in order to put any resistance we please into the circuit, we have merely to connect the resistance-box so that the current flows through it, and pull out the plugs from the gaps marked with the required resistances.

* When the plug is in place, of course some of the current runs through the wire, but practically the whole runs straight across the plug, and the wire coil only reduces an already infinitesimally small resistance.

The coils included in the box are, as in boxes of weights, of such amounts as shall make it possible to aggregate any required resistance between the smallest and twice the largest provided.

Thus there may be coils of 1, 2, 2, 5, 10, 20, 20, 50, &c., ohms, or coils of 1, 1, 2, 5, 10, 10, 20, 50, &c., ohms; or coils of ·1, ·2, &c., ohms may be supplied.

74. Precautions in using the box. 1. There must be no dust on the top which may impair the insulating quality of the ebonite.

2. Since the plugs are slightly cone-shaped, and the holes also taper, a slight screwing motion as the plugs are inserted will ensure perfect contact. The plugs must not be forced or the heads may be broken in removing them.

3. Since the coils are plastered with solid paraffin, on no account whatever must a considerable current be allowed to pass through any of them: even a small current flowing for a long time may do harm.

This is because, as will be seen later (p. 174), the passage of an electric current through a wire heats it, and (see p. 128) this changes its resistance, even if the rise of temperature is not enough to melt the paraffin.

In case it is necessary to insert a resistance in a circuit through which a large current is required to flow, coils made of spirals of platinoid wire, uncovered, and supported only at the ends, so that the air may circulate freely through them, are generally used, or at any rate wire insulated with silk and wound on a bobbin without any covering.

75. In Experiment 47 we were only provided with one standard resistance and could not measure the resistance of any given conductor: just as we cannot weigh a pint of water with scales and a 1 lb. weight, although we can find out how much water weighs 1 lb., and so, perhaps, deduce by calculation the weight of 1 pint.

If we are provided with scales and a box of weights, we can find the weight of 1 pint of water with an error less than the smallest weight in the box. So if we have a resistance-box of which the smallest resistance is 1 ohm (or ·1 ohm), we can find the resistance of a conductor with an error less than 1 ohm (or ·1 ohm).

EXPERIMENT 48. **To measure a resistance by the method of substitution.** Run a current from a simple chromic acid cell through a simple galvanometer *of low resistance*, and the conductor

whose resistance is required: e.g. 1 metre of No. 36 platinoid wire. (Remember to cut off more than 1 metre to allow for the pieces under the binding screws. Wire so brittle and thin as this should be wound round a screw of paper or piece of wood directly its length has been measured.)

Note and record the deflection of the galvanometer and substitute for the conductor, whose resistance is being measured, a resistance-box.

Before joining up the resistance-box pull out a plug so as to include some large resistance, and when coupled up take out the next smaller resistance before cutting out the one first included, and so on.

This will prevent too large a current being taken from the cell, which might polarize to some extent.

Then deal with the resistances exactly as you would with the weights in a box, subtracting and adding resistances in regular order until you find the resistance that allows a current to pass capable of deflecting the galvanometer to the same degree as before.

The resistance included in the box will be that of the given conductor; but the degree of accuracy will of course be no greater than that in Experiment 47.

CHAPTER VI

ELECTRIC CURRENTS

76. WE have hitherto used an instrument for comparing currents which we have called a galvanometer, but which does not truly deserve the name, since it is not well adapted for *measuring* currents. We must now provide ourselves with some means of doing this; i.e. we must be able to say how many times one current is greater than another, and we must fix on some current as a unit, to which we can refer all currents with which we have to deal.

We are not provided with an electrical sense by which we can appreciate the flow of a current directly by our senses; hence we must measure a current by one of the effects it produces. The most noticeable of these effects are—

(1) To produce a magnetic field round the conductor through which it flows (p. 130); the effect employed in a galvanometer.

(2) To heat the conductor more or less; as is seen in 'electric lights' where the filament in the glow-lamp is made white hot by the current.

(3) To split up any chemical compound through which it is made to flow; this effect we will now examine.

EXPERIMENT 49. **Electro-deposition of copper.** You will need two jars of copper sulphate solution, with two copper plates in each so arranged that they face one another at a small distance apart, that one at least can be easily removed, and that they can be fixed firmly enough to prevent movement during the experiment.

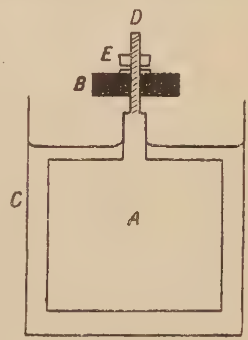


Fig. 53.

The simplest way is to fix each of the two plates (*A*, Fig. 53) into a bar of wood or ebonite (*B*) which lies across the top of the jar of solution (*C*), by means of a thick rod (*D*), soldered or riveted to the plate, passing up through the bar and threaded at the top to carry a pair of nuts (*E*), by means of which it may be held on the bar and attached to a wire.

The plates should be as large as may conveniently go into the jar; about 5×8 cm. will be enough, but the larger the better *, and they should be less than 1 cm. apart.

The solution of copper sulphate must not reach up to the solder.

The solution should be made up of the following proportions :—

Crystals of copper sulphate	150 grms.
Water	1000 c.c.
Concentrated sulphuric acid	15 c.c.

This should be kept in a special bottle, and must not be used in a Daniell's cell, since it would be contaminated with zinc sulphate.

Such an arrangement is called a **voltameter** because it serves to measure the current furnished by a voltaic cell.

You will need one such voltameter in several subsequent experiments; in this you will need two, or one of this kind and a rough temporary one (formed of two fair-sized copper plates, supported in a jar of the above solution so as to be parallel to one another).

Now connect together in series these two voltameters, a simple galvanometer wound with a few turns of copper wire, and a simple chromic acid cell, and let the current flow for a minute. Examine in each voltameter the plate by which the current *leaves* the cell. There should be a thin deposit of new copper all over the immersed part of each plate; if not, either no current was flowing, or the plates were not clean and must be rubbed with emery cloth and a fresh start made. If, however, there is a kind of sandy mud on either plate, the current is too strong and must be reduced by including in the circuit a piece of thin platinoid wire of suitable length.

When a satisfactory deposit has been obtained, the two plates must be dried and weighed accurately (*at least* to a centigram). Record the weight of each. The best way to dry them is to pour a little methylated spirit on them, or dip them in a beaker of the spirit, and then blow air on them with the bellows of a blowpipe.

Be careful not to touch the plates with your fingers from the time that they are cleaned or the first deposit is formed, as the film of grease so produced will prevent the deposition of copper.

Replace the plates, taking care that the circuit is so arranged that the current leaves each cell by the plate which has been weighed. Leave the current running for about a quarter of an hour (the longer

* If the plates are too small for the current passing through them, the copper instead of being deposited in a good adherent form is sandy and falls off in a kind of mud.

the better, a period which may be profitably spent in reading the following articles).

Take out and dry and weigh the plates as before, and determine the total quantity of copper deposited on each plate.

Is it the same on each?

77. Coulomb and ampere. All experiments like this show that when the same quantity of electricity passes through a series of such voltameters the amount of copper deposited in each is the same, in spite of differences in the size or distance apart of the plates, &c. Hence it is reasonable to take the quantity of copper deposited as the measure of the quantity of electricity which has passed through. The name given to the unit quantity of electricity is a Coulomb; it would seem convenient to take for the unit that quantity which deposits some round number of grams of copper in its passage; but for reasons to be explained later (see p. 104) the coulomb is taken as the amount of electricity which deposits ·000328 grm. of copper in its passage.

So we can determine how many coulombs have flowed through a voltameter by dividing the weight of copper deposited (in grams) by the number ·000328.

Now the magnitude of an electric current clearly depends on the quantity of electricity which passes a fixed point of the circuit in a given time; so it is natural to measure the current in a circuit by the number of coulombs which passes round it in one second. The unit current is called an Ampere, in honour of Ampère (Professor at Paris from 1809 to 1836).

For the present *, then, we will define the *ampere*, as being *the steady current which deposits copper at the rate of* ·000328 *gram per second.*

Experiment 50. **To measure a current in amperes.** Cause the current to pass through a voltameter, as in Experiment 49; observe the exact times at which the current is started after the plate has been weighed, and at which it is stopped before the final weighing; call the time during which the current has flowed t secs., and the weight of copper deposited m grms.

Then we know that

1 ampere deposits ·000328 grm. in 1 sec.;

$\therefore$ 1 grm. would be deposited in 1 sec. by $\dfrac{1}{\cdot 000328}$ amps.

* In the legal definition of an ampere, ·001118 grm. of silver is substituted for ·000328 grm. of copper.

$\therefore$ m grm. would be deposited in 1 sec. by $\frac{m}{\cdot 000328}$ amps.

$\therefore$ m „ „ „ „ t „ $\frac{m}{\cdot 000328 \times t}$ amps.

This then is the value of the current to be measured, if it was steady throughout the experiment; if not, it is its average value.

79. Calibration of a galvanometer or ammeter. We have now arrived at a satisfactory method of measuring an electric current, but one which in everyday practice would be intolerably tedious. An obvious way of shortening the process is to 'calibrate' a galvanometer, i.e. to find what current in amperes corresponds to each degree of deflection, by making a series of experiments like Experiments 49 and 50 with different currents. With a galvanometer so calibrated we could rapidly measure a current in amperes. The series of experiments for each galvanometer would be a lengthy one, but could of course be shortened by plotting the results of a small number on squared paper, drawing a smooth curve through the points so found, and using this calibration curve.

In practice, once one really well-made galvanometer has been carefully calibrated, the calibration of any other is effected by coupling it in series with the standard galvanometer and running various currents through them, noting the reading of each.

Such galvanometers are often graduated in such a way that their pointers move, not over a scale of degrees, but over one marked in accordance with the calibration in amperes; the galvanometer is then said to be 'direct reading,' and is usually called an **ampere-meter** or **ammeter.**

Ammeters are made in various forms, but are commonly mere galvanometers adapted so as to be portable, or not to be affected by neighbouring magnets.

The currents in use in a laboratory do not ordinarily exceed an ampere, and usually range from ·5 amp. down to about ·01 amp.; hence the most useful ammeter is one with some such range.

EXPERIMENT 51. **To check the accuracy of an ammeter.** You will need a really constant cell, such as a storage cell from which a little current has been taken. Remember that the internal resistance of a storage cell is so small that, if it is short-circuited even for a second, it is damaged. If no storage cell is available, a Daniell cell will serve quite well if it has been set up for some time, during which it has been short-circuited so as to attain a steady state.

Couple in series a constant cell, a copper voltameter as described on p. 72 *d*, the ammeter to be tested, a plug key or other switch, and if necessary such a length of platinoid wire (or rough resistance coil which will not be damaged by having a current through it for some time) as to make the current register the desired amount on the ammeter.

Make a preliminary deposit on the plate you propose to weigh as in Experiment 49, and see that the character of the deposit of copper on the plate is satisfactory.

Dry and *weigh as accurately as you can* the plate by which the current leaves the voltameter; replace it, and by an accurate watch note the time at which you join up the circuit; it is convenient to do this at some exact minute.

Read the ammeter as soon as it is steady, and do this at every successive minute until you stop the current.

The length of time during which the current must be kept running depends on the magnitude of the current, and to some extent on the accuracy with which you can weigh *.

Supposing that the current is constant throughout the whole period, the calculation proceeds as in Experiment 50. If it varies a great deal the experiment fails.

If it varies a little, and the falling off (or increase) has been regular, the average current deduced from the weight of copper and the time should agree with the average of the readings: if they do not, you will get the error of the ammeter not for a particular graduation, but averaged over a small range, which would probably be the same as at any one of the graduations included in that range.

CHAPTER VII

Magnetic Methods of Measuring Currents

Some of the following articles are alternative; those which deal with the tangent galvanometer are marked T. *against the number of*

* Assuming you can weigh to 1 mgm. (which needs a glass-cased balance) and desire an accuracy of 1 % in your result, you must have at least 1 dgm. or ·1 grm. of copper deposited.

Now 1 amp. deposits roughly ·02 grm. per min., so that 5 min. would suffice for such a current: if your current be only ·2 amp. you must let it run for 25 min., and so on.

the article, those involving the use of a moving coil instrument are marked M. *Articles not so marked are common to the two parallel courses.*

80. In the case of two forms of galvanometer the number of amperes flowing through and the deflection produced are connected by simple laws.

The actual number of amperes which will deflect the needle through a certain angle depends on the form and size of the instrument, the number of turns of wire, &c., that is, on the sensitiveness of the instrument; but when this has been found by experiment (as in Art. 79) for one angle of deflection, the current corresponding to all other angles can in these instruments be deduced by simple calculation. This is not the case with the galvanometer described on p. 49.

If we decide that the numerical magnitude of an electric current is measured by the rate at which it deposits copper, no amount of *theoretical reasoning* can possibly lead us to a law connecting the deflections of the needle of a galvanometer, and the currents running through it; the law must be determined by experiment, as follows.

M. 81a. Moving coil galvanometer. Experiment 34 (p. 45) showed that when a wire carrying a current was held firmly near a movable magnet pole, the latter moved; the wire exerted a force on the pole, and there must have been an equal and opposite force reacting on the wire (though too small to be felt in that experiment). So that if the pole had been fixed and the wire had been free to move, the wire would have moved.

Now the compass-needle creates a field of magnetic force in the space round it, and the action between the electric current and this magnetic field is the only way in which the needle can affect the wire; so we see that if a current flows through a field of magnetic force there is a mechanical force on the conductor carrying the current. The magnetic field round a compass-needle is a complicated one; it is simplest to deal with a 'uniform' field, in which all the lines of force are parallel and the magnetic force on a pole is everywhere the same. It is an experimental fact that if a straight conductor carrying a current is placed at right angles to these lines of force, it is acted on by a force tending to move it in a direction at right angles, both to the conductor and the lines of force; see fig. 53 *a*, where the conductor will be urged to move broadside towards the spectator.

It is found further that the magnitude of this force is directly proportional to the length of the conductor so acted on, and to the strength of the magnetic field, and to the magnitude of the current *as measured by the rate at which it deposits copper.*

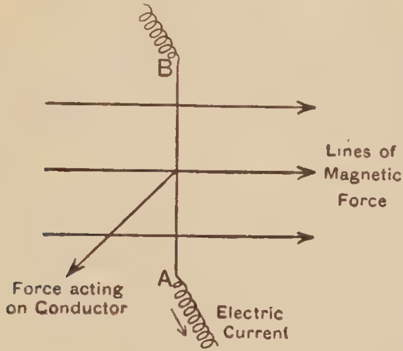


Fig. 53 *a.*

In this form the experiment would be difficult to carry out; a more practicable form will now be described.

If we explore (by iron filings) the magnetic field near the arrangement shown in Fig. 53 *b*, which consists of a cylinder of soft iron (*O*) lying between two strong permanent magnet poles (*N* and *S*) whose ends are cut out to form parts of a concentric cylinder, we shall find

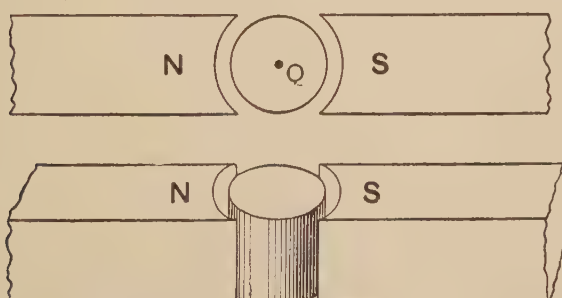


Fig. 53 *b.*

that the lines of force in the 'air gap' between the poles and the cylinder are as in Fig. 53 *c*, all the lines passing through this air

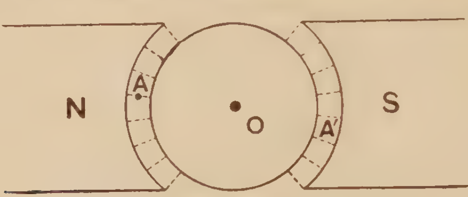


Fig. 53 *c*.

gap being directed towards or radiating from *O*, the centre of the cylinder. So the field near a point *A* is exactly as if, instead of this arrangement of permanent magnets and soft iron, a very strong single magnet pole were situated at *O*; in this case the magnetic force at *A* depends on the distance of *O* from *A* (see p. 23), and therefore is the same for all positions of *A* at the same distance from the centre *O*. Hence, if we bend a wire into the shape *CAC'* and support its ends in cups in the centre line of *O* (as in Fig. 53 *d*, where *N* and *S* are omitted

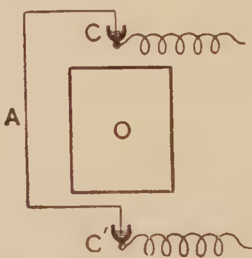


Fig. 53 *d*.

for clearness), then the magnetic field at *A* remains of the same strength as the wire turns on its pivots, provided that *A* lies in the left-hand air gap. If we pass a current through *CAC'* we have a conductor carrying a current and free to move at right angles to itself and to the lines of magnetic force, and always in a magnetic field of the same strength; so we can experiment on the connexion between the mechanical force tending to move the conductor and the number of amperes flowing along it.

But we can make the instrument more sensitive. Suppose the current flows from *C* to *C'*, i. e. into the paper in Fig. 53 *c*. Now the

lines of force at both A and A' in that figure run from left to right, so this wire at A or A' would be pushed in the same direction, either up the paper or down it. But if the current runs into the paper when the wire is at, say, A, and out of it when the wire is at A', the forces would in each case tend to turn the wire *in the same direction round* O; so if we make a rectangle of wire and support it as in Fig. 53 *e*, the forces on each side tend to twist this rectangle round in the same way, and with double the strength as compared with the single wire.

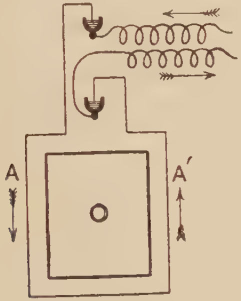


Fig. 53 *e*.

We can neglect the forces on the part of the wire which does not lie in the air gap, because the magnetic field there is comparatively weak, and what there is of it is not at right angles to the conductor.

As in the case of the simple galvanometer, we can increase the effect by using a coil instead of a single turn, and we can further increase it by using a very strong magnet for NS. Though the force is still very small for moderate currents, it can be measured either by suspending the coil by means of a narrow, thin, flat strip of metal, or by mounting the coil on pivots and using thin spiral springs, like the balance spring of a watch; in both cases the springs tend to keep the coil in the direction NS, while the reaction of the magnetic field on the current tends to twist it round. The force tending to twist the coil is directly proportional to the angle through which it succeeds in deflecting it from its central position; for it is a well-known property of springs, that the distortion is directly proportional to the force causing it. So although we do not determine the actual magnitude of the force produced on the wire when it carries a current, we can easily compare the forces acting on it for different currents.

If we measure these currents by the method of Experiment 50, we shall find that in any one instrument *the angle of twist is directly proportional to the rate at which the current deposits copper.* In other words, the force on a conductor carrying a current in a magnetic field to which it is at right angles is directly proportional to the current measured in amperes.

Having proved this, we see that for such a galvanometer we have only to measure one current passing through it, and observe the deflection of a pointer attached to the coil; hence find by division the current corresponding to one degree of deflection, and the scale can then be marked off for all currents within the range of the instrument (i. e. those which do not deflect the coil beyond the air gap).

The ordinary ammeter is usually of this form; when needed to measure fairly large currents only a known fraction is allowed to pass through the instrument, as will be explained in Art. 117; by measuring this the total current can easily be calculated. By suspending the coil by thin wires, by which the current passes to and from the coil, and observing the deflection by means of a mirror attached to the coil, very minute currents can be measured; this form is called the D'Arsonval galvanometer. A very convenient form is Paul's single pivot galvanometer, in which the coil is supported on a single pivot, and the controlling spiral springs, by which the current enters and leaves the coil, are very thin. The deflection is measured by a pointer moving over a scale; the instrument is very compact, can be moved about with safety, and is ready for use without adjustment; yet it is as sensitive as many mirror galvanometers, and shows the current direct in thousandths of an ampere; it can also be made sufficiently sensitive for use with the Wheatstone's bridge (see Art. 125), &c.

T. 81b. Tangent galvanometer. Experiments establish the fact that if a current flows *along a wire, bent into the form of a circle, a magnetic force is produced at the centre of the circle, acting at right angles to the plane of the circle, which is directly proportional to the current flowing in the wire* (*as measured by its rate of copper deposition*).

In previous experiments you have seen that when a current flows round a single turn of wire, such a magnetic field is produced at the centre (since a compass-needle placed there had its N. pole thrust one way, and its S. pole thrust the other, in directions at right angles to the plane of the coil).

What is new in the above statement is that this magnetic force is exactly proportional to the *magnitude* of the current in amperes.

Such a conclusion is of the utmost importance, and it must not be supposed that it could have been predicted. There is no theoretical reason why the magnitude of the magnetic force should not vary as the square, or as the square root, of the magnitude of the current as measured by its rate of copper deposition.

T. 82. Assuming for the present* the truth of this law of nature (it was discovered by Faraday, Professor of Physics at the Royal Institution), we can deduce by mechanical reasoning the manner in which the deflection will vary with the current in a given galvanometer if the coil consists of circular turns of wire, which are large compared with the size of the needle.

(The student should examine an ordinary tangent galvanometer before reading the following articles.)

Fig. 54 represents a horizontal section through the centre of a 'tangent galvanometer.'

$A\,A'$ is the section of the vertical circular wire coil (the current coming out of the paper at A and running into the paper at A').

NS is the compass-needle, which must be so short (not more than $\frac{1}{10}$ of $A\,A'$) that N and S may both be treated as if at O, the centre of the circle of wire.

$A\,A'$ is placed in the magnetic meridian, so that until a current flows NS will lie in the line $A\,A'$.

Suppose that a current of C amperes flows round the coil, and that this produces a magnetic force of F dynes on unit-pole at O.

Then, by the above law, F is proportional to C, and we may take

$$F = G.C$$

where G is some constant number depending on the size of the coil of wire.

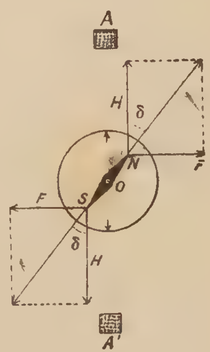


Fig. 54.

The compass-needle will be deflected through an angle, δ, until the magnetic forces of the earth's field tending to keep NS parallel to $A\,A'$ is balanced by the magnetic forces of the current tending to set NS at right angles to $A\,A'$.

* We can verify it ourselves later, by repeating Experiment 54 for different currents.

Suppose that the strength of each pole of the compass-needle is m units, then the force of the current on each pole is

$$F m \text{ dynes.}$$

It was shown in Art. 22, Part I (p. 24 *b*), that if E represents the earth's attraction on each of the poles,

$$F m = E \tan \delta.$$

Now H is usually taken to represent the earth's (horizontal) force on a *unit*-pole,

$$\therefore \quad E = H m.$$

Hence $$F m = H m \tan \delta,$$

or, $$F = H \tan \delta.$$

But $$F = G C.$$

Hence, finally, $$C = \frac{H}{G} \tan \delta.$$

Both H and G are numbers that are constant for the same place and the same galvanometer, so that this formula shows that under these circumstances *the current running through the coil is always proportional to the tangent of the angle of deflection of the needle.*

T. 83. Adjustment of the tangent galvanometer. A moderate current flowing round a single turn of wire of large radius will obviously produce only a very feeble magnetic 'force-intensity *' at its centre (Experiment 38), and therefore a small deflection of the needle.

If it is desired to measure small currents, in other words to increase the sensitiveness or sensibility of the instrument, it is usual to employ a large number of turns of wire in the coil, and to adopt means of measuring accurately an exceedingly small angle of deflection.

In all cases, since the needle is short, it is usual to attach a long pointer to it, so that the scale of degrees may be an 'open' one: and to put a fixed horizontal mirror below this pointer to avoid 'errors of parallax' in taking a reading (by placing the eye so that the pointer appears to cover its own image).

Since the first operation with a tangent galvanometer is to place the plane of the coils parallel to the needle, and since the breadth of the coils would make it impossible for an eye placed vertically above the centre to see the end of the needle, the pointer is usually fixed at *right angles to the needle*. The zero of the scale over which the pointer moves is then along a line at right angles to the plane of the coil.

The compass-needle is often hung by a fibre of unspun silk, to avoid

* i. e. the force that would act on a unit magnetic pole if one were placed at the point in question.

the friction which exists even with the best agate cap on a steel needle-point. This fibre introduces errors due to its resistance to a twisting force, which makes the current seem less than it is, and if it has been twisted, may even slightly deflect the compass from the magnetic meridian when there is no current flowing. This latter error can be eliminated by reversing the current in the galvanometer and taking readings on both sides of the zero, as will be described later.

Many tangent galvanometers are provided with several different coils, all wound on the same circular frame, of different numbers of turns; each is connected to its own binding screws, so that any one may be used.

One may have 500 turns, another 50, another 1, so that the same instrument may be used to measure currents ranging from ·005 amp. to 5 amps.

EXPERIMENT 52. **To compare currents by a tangent galvanometer.** Take a simple chromic acid cell, a resistance-box, and a tangent galvanometer; one having about 50 turns and a small internal resistance (about 1 ohm) is convenient.

Let us compare the current which the cell is capable of driving through the galvanometer and 50 ohms with that through the galvanometer and 100 ohms.

First adjust the galvanometer. The needle must be made to swing freely, if necessary, by adjusting the levelling screws or the length of the fibre.

The whole galvanometer, or the coils if they are movable separately, must be turned until the needle is parallel to the plane of the coils. If the instrument is accurately made this will occur when the pointer of the needle points to the zero of the scale.

If there is an inaccuracy it can be corrected by a method to be described later. It is best to start with the pointer at 0°.

If the two ends cannot be made to stand at 0° together, put one end at 0° and use that to measure the deflections.

Now couple up 'in series' (see Fig. 50 and p. 70) the cell, the galvanometer, and the resistance-box with 50 ohms in circuit. Note the angle of deflection of the needle, and look out in a table of tangents (see Appendix) the value of the tangent of the angle of deflection. This will *not* be the number of amperes flowing, but will be proportional to it; i.e. the number of amperes multiplied by some number which is always the same for that galvanometer.

Repeat the experiment with 100 ohms in the box. Compare the

currents by dividing one by the other: the result is the number of times one current is as large as the other.

T. 84. The result of Experiment 52 may be in error because, among other reasons:—

(1) The pointer may not be at right angles to the needle.

(2) The fibre may be twisted before the current flows.

(3) The pointer may be bent, or the needle and pointer not concentric with the circular scale of degrees.

(1) and (2) will result in the coils not being in the meridian.

(3) will cause the readings of the two ends of the pointer to differ.

The easiest way to deal with these difficulties is to reverse the connecting wires to the galvanometer, so that the current flows in the opposite direction through the galvanometer; if the deflection is then the same on the other side as at first, errors (1) and (2) are not serious.

The reading is usually different, and it may be remedied by readjusting the pointer; but if the difference is small it is best to allow for it by always reversing the current and taking the average deflection.

(3) may be eliminated by adjustment or by reading both ends of the pointer.

Thus, to measure the deflection you should read both ends of the pointer, then reverse the current in the galvanometer, read both ends again, and take the average of all four angles for the deflection.

85. Commutator. The process of reversing the current in an instrument as above described has frequently to be carried out, and

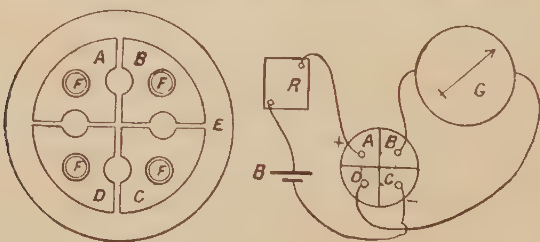


Fig. 55.

as it is tedious to uncouple and recouple two wires in binding screws, a key called a 'commutator' is used.

The simplest form of this consists of a kind of double plug-key, as shown in Fig. 55.

A, B, C, D are four solid brass sectors, supported on a non-conducting base E, separated as the blocks in a resistance-box (see Fig. 51, p. 72).

Each sector carries a binding screw (F).

Two plugs are provided, so that A can be joined to B, and C to D: or, A to D and C to B.

The wires from the instrument in which the current is to be reversed are joined to diagonally opposite sectors, as B and D; and the other wires, by which the current comes and goes away, to A and C, as in Fig. 55.

If the plugs be put between A and B, and between C and D, the current will flow from B to the galvanometer; but if the other way, the current in the galvanometer only will be reversed.

Caution. Care must be taken, in changing the plugs, not to short-circuit the battery by putting one plug into its new place before removing the second from its old one.

T. 86. Reduction factor of a tangent galvanometer. We have proved that for various currents in the same tangent galvanometer the current is always *proportional* to the tangent of the angle of deflection.

If, then, we can find the actual deflection produced by any one current, whose value is known in amperes, we can use the tangent galvanometer to measure any other current.

For we always have $C = \frac{H}{G} \tan \delta$ (see Art. 81) where $\frac{H}{G}$ is a number, which for convenience we will write K, and we will call it the **reduction factor** of the galvanometer.

$$\text{Since } C = K \tan \delta,$$

$$\therefore \quad K = \frac{C}{\tan \delta}$$

If we can find one pair of corresponding values for C and δ, we can find K, and the value of $K \tan \theta$ will be the number of amperes that gives the deflection θ.

It should be fully understood that the value of the reduction factor of a galvanometer depends upon H, so that if the magnetic force varies from point to point of the laboratory (as it always does, often to the extent of 10%), the reduction factor will also change in proportion. This constitutes the inconvenience of a tangent galvanometer as a current measurer.

EXPERIMENT 53. **To find the reduction factor of a galvanometer by comparison with an ammeter.** The principle of this is simple; it consists in running a current through a tangent galvanometer and an ammeter in series, and comparing the readings. Thus we find one pair of values for C and δ in the equation

$$C = K \tan \delta,$$

which enables us to calculate K.

The details depend largely on the kind of ammeter which is available.

If it is graduated between 0 and 1·0 ampere, we must use a coil of the tangent galvanometer, which consists of not more than two or three turns; if the ammeter ranges say between ·01 and ·1 ampere, then a coil of thirty or fifty turns will probably be better *.

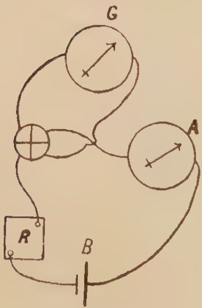


Fig. 56.

Connect in series a cell B, the ammeter A, and a resistance R, such as a rheostat or a piece of platinoid wire, or a rough resistance coil, also a commutator which can send the current in either direction through a tangent galvanometer G (see Fig. 56).

Adjust the resistance until the current gives a satisfactory deflection on the ammeter; and see that the deflection of the tangent galvanometer falls between reasonable limits.

It is quite possible that the current may be too small even if R is removed; in that case you must get another cell, and put it 'in series' with the first; i.e. connect the carbon of one cell to the zinc of the other, and treat the zinc of the one and the carbon of the other as if they were the poles of a cell. Fig. 63 shows two cells connected in

* It may here be mentioned that, since the value of $\tan \delta$ may be anything from 0 to an infinitely great number according to the value of δ, a tangent galvanometer with a coil of any number of turns will be able to measure a current of any magnitude that is passing through it; but as a matter of practice a tangent galvanometer gives the best results when it is measuring such a current as deflects the needle to an angle between 30° and 60°, and it is almost impossible to get an accurate value for a current giving a deflection of more than 75°, or less than about 10°.

Hence the need of several coils, so that one instrument may deal with a wide range of currents.

series. These will drive a greater current through G and A, provided that the resistance to be overcome by the current was mostly in G and A, and not in the cell itself.

When the deflection is constant, take as accurately as you can readings of both G and A, then reverse the current in G and read again.

Take the arithmetic mean of the four values of the deflection (δ) of the tangent galvanometer, and substitute this, and the current in amperes (C), in the equation $K = \frac{C}{\tan \delta}$.

T. 87. If no ammeter is available, the reduction factor of the tangent galvanometer can be found from a measurement of the copper deposited by a current running through it, as in the following experiment.

EXPERIMENT 54. **Direct determination of the reduction factor of a tangent galvanometer.** This experiment is carried out exactly as Experiment 50, except that a tangent galvanometer is to be used instead of an ammeter; the galvanometer should be included in the circuit by means of a commutator (see p. 84) as in Fig. 55.

At the end of each minute, when a reading has been taken, the commutator should be moved to reverse the current in G ready for the next reading; but as this would stop the current for some time, a plug commutator is not permissible.

If a plug commutator is to be used you must determine in the preliminary experiment the deflection on the one side corresponding to that on the other, which is to be used during the actual experiment, and you must not disturb the commutator while the weighed amount of copper is being deposited. The average of four readings of the deflection is of course to be used, not the deflection on the one side as observed during the experiment. Knowing δ and having calculated C as in Experiment 50 and 51, you can obtain K from the equation

$$K = \frac{C}{\tan \delta}.$$

T. 88. Value of the reduction factor as depending on the number and radius of the turns of wire. We have considered (on p. 80) the connection between the magnetic force on unit-pole at the centre of a circular turn or coil of wire, and the magnitude of the current flowing in it, for variations in the magnitude of the current.

We must now consider the effect on that force of changing the number of turns or radius of the coil, keeping the current the same.

This again is purely a matter of experiment, but the experiments needed to verify the law that has been discovered are very simple, and you can easily perform them with accuracy enough to satisfy yourself that the law is true, provided that you have available a tangent galvanometer adapted for the purpose.

In its simplest form this consists of a compass-box, as in an ordinary tangent galvanometer, which is mounted at the centre of several concentric coils of wire, all mounted to lie in one plane. This may easily be done by attaching all to a board, in which a hole is cut to receive the compass-box and its fittings.

The ends of each coil must be brought out separately, so that currents can be sent in either direction through any arrangement of them in series or otherwise. It is convenient to have one coil, *A* (Fig. 57), of double the radius of another, *B*.

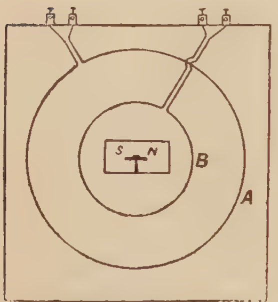


Fig. 57.

The magnetic force at the centre *O* can be measured (see p. 24) by the tangent of the angle of deflection of the needle.

Suppose a current to be sent round *one* turn of the coil *B*. (It will be necessary to include in the circuit an ordinary current-measurer of some sort, to see that the current does not vary when the different resistances of the various coils are included; this may be prevented by varying a resistance also included in the circuit for that purpose.)

Suppose the same current to be next sent round two and then three turns, and so on.

It will be found on taking the tangents of the deflections, that these are in the ratio of 1, 2, 3, &c., showing that a current running round two turns produces at the centre twice the magnetic force-intensity * that it does when running round one of the same radius, and so on: or, generally, *the magnetic force at the centre is directly proportional to the number of turns in the coil.*

By comparing the tangents of the deflections produced by the same

* See p. 82 for the meaning of magnetic force-intensity.

current when traversing one turn of coil A, and of coil B (A having *twice* the radius of B), it will be found that the former current produces only *half* the force produced by the latter; and if you have a coil of any other radius with which to experiment, you will find that, for the same current, the tangent of the angle of deflection is inversely proportional to the radius of the coil; so we may say that *the magnetic force at the centre is inversely proportional to the radius of the coil.*

T. 89. A simple experiment will show the combination of these two variable quantities, radius and number of turns.

In Fig. 57, suppose that A consists of two turns and has a radius double that of B, which has only one turn of wire. If a current be run round A in one direction and round B in the opposite direction, their effects will be found exactly to neutralize one another, producing no deflection at all of the needle at O.

This is a more delicate test of the accuracy of the law than we can make by sending the current in the same direction through A and B successively, and measuring and comparing the deflections. But remember that each part of the law must be verified separately, since the above 'differential' experiment would have produced the same absence of deflection if the magnetic force-intensity had varied, let us say, as the square of the number of turns, and inversely as the square of the radius.

T. 90. We can then sum up our experimental results for the variations of current, radius, and number of coils as follows:—

The magnetic force at the centre of a circular coil of wire varies directly as the current, directly as the number of turns, and inversely as the radius of the coil.

We assume that all the turns of the coil have the same radius, and lie in the same plane. This of course cannot be realized in practice, but the law will hold approximately for a coil whose breadth and depth are small compared to the radius of the circle.

T. 91. A further experiment is needed to give us a *numerical* connection between the magnetic force-intensity and the number of amperes flowing round the coil; all the previous experiments having been only to find the effects of varying the quantities involved. We may put the above law in the form of an equation thus:

$$F = A \times \frac{n}{r} \times C,$$

where F = magnetic force at centre of coil,
n = number of turns of wire in the coil,
r = radius of the coil,
C = current flowing in the coil,
A = some number to be determined experimentally.

This number A depends on the units in which we express F, r, and C, as well as on the physical connection between the copper-depositing and magnetic-field-producing powers of an electric current.

Let us decide to express F in the same units as are used to measure H (see p 26), i. e. as the number of dynes that would be exerted on a unit magnetic pole at the point in question; r in cm., and C in amperes; then an accurate experiment conducted on the lines of Experiment 54 will give us a value for A which will be ·6282; this may be written $\frac{2\pi}{10}$. (The more accurate the experiment, the nearer the result comes to this fraction.)

The result of all these experiments for any tangent galvanometer is a valuable formula, worthy to be remembered:

$$F = \frac{2\pi}{10} \times \frac{n}{r} \times C.$$

T. 92. Calculated value of reduction factor. We have seen (p. 82) that the deflection δ of the needle of a tangent galvanometer, which is kept in its undeflected position by the magnetic field of force H, is connected with the magnetic force F which produces the deflection, by the equation

$$F = H \tan \delta,$$

$$\therefore \quad \text{from Art. 91} \qquad H \tan \delta = \frac{2\pi}{10} \times \frac{n}{r} \times C.$$

$$\therefore \qquad C = \frac{10 H r}{2\pi n} \times \tan \delta.$$

i. e. the reduction factor of a tangent galvanometer is

$$\frac{10 H r}{2\pi n},$$

and can be calculated when we know the dimensions of the galvanometer and the value of H at the place of observation.

EXPERIMENT 55. **To calculate the reduction factor of a tangent galvanometer.** Measure the radius of the turns of wire forming the coil: if there is more than one layer, measure the inner and outer diameter of the whole coil and find the average radius.

In any case the radius of the central line of the wire should be taken.

Ascertain the number of turns; these may be visible or may have been recorded when the instrument was made.

It will probably be accurate enough to take H as having the value

·18 (dynes on a unit magnetic pole), although it varies for different places and at different dates, for the error of the determination of the reduction factor will not be likely to be much less than 5 %.

Then substitute these values in the formula for the reduction factor (K) of the galvanometer,

$$K = \frac{10\,Hr}{2\,\pi\,n}.$$

T. 93. Use of control magnet. Some tangent galvanometers are provided with a permanent magnet, usually adjustable on a vertical rod fixed above the centre of the coil.

The magnet is horizontal and can be raised or lowered, and turned round to any angle. This allows us to modify H to a large extent, and so to extend the range of sensitiveness of the galvanometer.

Provided that during an experiment the control magnet is not moved, the tangent of the deflection of the needle will be proportional to the current flowing; but the reduction factor will, of course, not have the same value as if the earth's were the sole controlling force.

The coils need not even be put in the magnetic meridian, but the control-magnet must be so adjusted before the experiment that the needle lies parallel to the plane of the coils.

94. Other galvanometers. We will now proceed to describe some other forms of galvanometers; as with voltaic cells, their description need not be taken at this point of the course, but may be referred to when occasion arises.

In cases where extreme sensitiveness is required it is possible to attain it by a combination of several devices, such as increasing the number of turns in the coil, weakening the force which has to be overcome by the magnetic effect of the current, and improving the methods for measuring the deflection of the needle.

The last two are provided for in the astatic and mirror galvanometer respectively.

95. Astatic galvanometer. In a 'simple' or tangent galvanometer the strength of the poles of the needle has no effect on the deflection, since weakening the needle lessens the force of the earth and of the current in the same proportion; it is better to have it as strongly magnetized as possible in order that the friction of the support may be of less influence.

Suppose, however, that to the needle which hangs at the centre of the galvanometer is rigidly attached (as in Fig. 58) another needle,

of equal magnetic moment, lying above or below the first, and parallel to it, but with its poles set the opposite way round.

If the second needle lies outside the coil, when there is no current flowing round the coil the earth's control on the one needle will be exactly neutralized by the other, and the system will not stand in any particular position. Hence this is called an 'astatic' system (ἀ, not, and ἵστημι, I stand). It will settle down in some direction determined by the exceedingly weak torsional force of the fibre *A* by which it is supported.

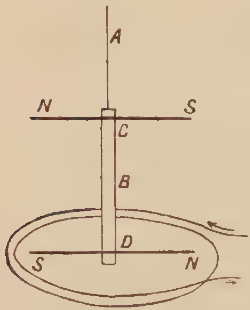


Fig. 58.

In practice, it is impossible to get or keep the two needles *C* and *D* of absolutely the same strength, so that in such a combination there will be a slight residual effect of the earth, tending to set it in the magnetic meridian.

Consider now the effect of a current in a coil surrounding only the *lower* needle. By an application of the corkscrew rule (see p. 50) to the lower needle, it may be seen that, as arranged in the figure, the right-hand end will be thrust out of the paper. On the upper needle the effect of the lower wires of the coil will be to drive the right-hand end into the paper; but the upper wires will tend to thrust the upper S. pole out of the paper, and, as they are nearer to the pole, their effect will be greater, so that, on the whole, the upper needle too tends to move so that the right-hand end comes outward.

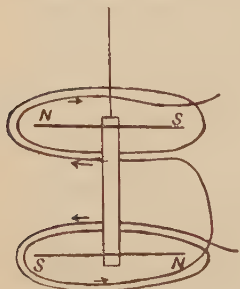


Fig. 59.
Astatic Galvanometer.

Thus the addition of the upper needle reduces the earth's force on the combination almost to nothing, and increases that of the current. As the controlling force is now not wholly the earth's force on the needle, which is constant in amount and direction, but is mainly due to the torsion of the supporting fibre, this form of galvanometer cannot in strictness be used as a *tangent* galvanometer; but for very small deflections, as in the mirror galvanometer, the tangent law is nearly true.

A still greater sensitiveness will be attained if the current passes

round both needles, in two coils wound in opposite directions, as in Fig. 59.

96. Mirror galvanometers. If a small mirror, either plane or concave, is fixed to the needle, and a beam of light is directed on it in a dark room, the reflected beam will act as pointer to the needle, turning, however, twice as fast as the needle.

In Fig. 60 NS is the mirror attached to the needle, AO the incident ray of light (which is fixed in position), OC the normal to the mirror, OB the reflected ray.

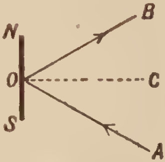


Fig. 60.

By the laws of reflection of light the angle AOC equals the angle COB.

If, then, the needle moves, deflecting the normal OC with it, the angle made by OB with OC changes as much as that made by OC with OA.

Thus, the angle between OB and OA changes twice as much as the angle between OC and OA.

In other words, since OA is fixed, the deflected ray moves through twice the angle that the mirror turns through.

The reflected beam strikes a scale, and either by the concavity of the mirror, or by a lens interposed in the path of the beam, an image of an aperture (through which the beam has passed before incidence on the mirror) is brought to focus on the scale. By putting the scale far from the mirror the movement of the image for a small deflection of the needle may be made as large as is desirable. The distance of the aperture from the mirror does not affect the sensitiveness.

It is not usual to measure the angle through which the needle turns; this would require a scale curved to the arc of a circle concentric with the centre of the needle, and specially graduated for a certain radius.

Usually a straight scale is used, graduated into any convenient equal lengths; $\frac{1}{40}$ of an inch is commonly used.

Since the angular deflection of the needle does not exceed about 2°, the number of those equal scale divisions traversed by the image is very nearly proportional to the tangent of the angle of deflection of the needle, provided that the mirror is nearly perpendicular to the incident ray. Hence, if the galvanometer is constructed so that the tangent of the angle of deflection is proportional to the current flowing round it, then the current is proportional to the number of scale divisions through which the spot of light is deflected. Since the angular deflection is very small in this instrument, the tangent law will be true even if the length of the needle is more than $\frac{1}{10}$ of the radius of the coil; but the needle must be made as small as possible.

97. The arrangement of the apparatus is as follows, the figure (61) giving a horizontal section, omitting all supports:—

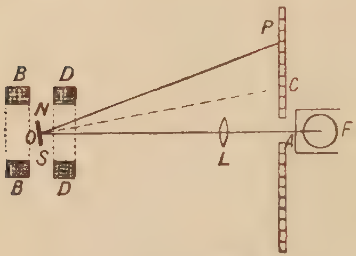


Fig. 61. Mirror Galvanometer.

F is the lamp, A the screen pierced by a small aperture (or a single wire may be substituted), C the scale of equal parts, L the lens for focussing the aperture on C.

$N S$ is the mirror, B and D sections of the coils, the planes of which are supposed to be vertical and parallel to the scale C.

P is the image of the aperture, $F O$ being the incident, and $O P$ the reflected ray.

Mirror galvanometers usually carry a control magnet as described on p. 91.

98*. We may now investigate the justification for taking the displacement of P as proportional to the angular deflection of $N S$.

Let $C O$ (Fig. 61) be the normal to the mirror, and let the angle $C O F$ (i. e. the deflection of the needle, if we assume that the undeflected position of the needle was parallel to the scale) be called δ.

Then we have, by definition of the tangent,

$$\frac{C A}{A O} = \tan \delta,$$

and
$$\frac{P A}{A O} = \tan 2 \delta.$$

Now $\tan 8° = \cdot 1405$ and $2 \tan 4° = \cdot 1398$, so that we make less than $\frac{1}{2}\%$ error in taking $\tan 8°$ as equal to $2 \tan 4°$, and hence, if $\delta°$ is not greater than about 2°, we may consider, since $\tan 2 \delta = \frac{P A}{A O}$,

that
$$\frac{P A}{A O} = 2 \tan \delta,$$

i. e. that
$$P A = 2 \times A O \times \tan \delta,$$

i. e. since $A O$ is constant, that $P A$ is proportional to $\tan \delta$.

99. Such a mirror galvanometer is most frequently used, not for measuring very small currents, but for indicating the existence and direction of such currents.

The most satisfactory methods of measurement are generally those in which the object aimed at is to balance apparatus in such a way that no current flows, rather than to measure the current produced; the former are called

'Null methods,' and examples will be found in the measurements of a resistance on p. 121, and of an electromotive force on p. 116. For such experiments the more sensitive the galvanometer the more accurate will be the result, and the fact that an astatic galvanometer does not truly obey the tangent law is no objection.

100*. Sine galvanometer. Since the radius of the coil of a tangent galvanometer must be large compared with the length of the needle, it is impossible to attain very high sensitiveness; but if the coil is mounted so that it can be turned about a central vertical axis, any galvanometer can be used as a *sine galvanometer*, whatever the shape or size of the coil. The only condition is that the control should be produced by a uniform magnetic field such as that due to the earth.

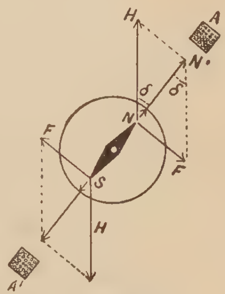


Fig. 62.

In order to measure a current, the process is not first to put the coil in the magnetic meridian and then to measure the deflection of the needle when the current flows; but the current is made to flow and then the coil is turned round after the needle until it overtakes it, i.e. until the needle lies in the plane of the coil. During this turning the needle will be deflected from the meridian more than it was when the coil lay in the meridian, but if the current is not too strong the coil will catch up the needle before it gets perpendicular to the meridian.

In this position there are two forces acting on each pole of the needle. (In Fig. 62 $A\,A'$ represents the section of the coil; $N\,S$ the needle, H the controlling force, and F the magnetic force due to the current in the coil.) The needle and coil are assumed to make an angle δ with the magnetic meridian when the coil overtakes the needle.

As in the case of the tangent galvanometer, the resultant of the forces H and F must lie along the needle.

Hence the angles $H\,N\,N'$ and $N\,N'F$ must both be equal to δ.

We know that the angle $N'N\,F$ is a right angle, since $N\,F$ is the direction of the force F which acts at right angles to the coil.

Hence, by the definition of the sine of an angle,

$$\frac{N\,F}{N'\,F} = \sin\,\delta.$$

But $$N\,F = F, \text{ and } N'F = N\,H = H.$$

$$\therefore \quad \frac{F}{H} = \sin\,\delta.$$

Again, F is proportional to the current, C, flowing in the coil, whatever the shape of the coil, and wherever n comes in the coil, since these two latter do not change; so that *C is proportional to sin δ.*

101*. There are two possible methods of measuring δ. We may have a pointer or vernier attached to the stand carrying the coil, moving over a fixed scale and showing the angle turned through by the coil. In this case the needle need not have a pointer moving over a graduated arc, but merely have a mark to show when it is in the plane of the coil. Instead of this we may have no scale to show movement of the coil, but may measure it by means of a scale fixed to the coil as in the tangent galvanometer, over which moves a pointer attached to the needle.

In this latter method the coil is turned while the current flows until the zero of the scale comes to the pointer; then the current is stopped, the needle returns to the meridian, and shows by its position how far the coil is deflected from the meridian.

Thus an ordinary tangent galvanometer may be used as a sine galvanometer (for currents which do not deflect the needle more than 45° when the coil is in the meridian.)

The student must of course be provided with a 'table of sines' for use with this instrument.

CHAPTER VIII

Electromotive Force

Experiment 56. Take a simple cell of copper and amalgamated zinc, and connect it to a sensitive moving coil galvanometer in series with a high resistance, or a tangent galvanometer wound with a large number of turns (say 500), of thin wire having a resistance of about 200 ohms. Failing these, a simple galvanometer wound with thin platinoid wire will do.

Put a little dilute acid in the cell so that the plates are both just dipping in it, and observe the deflection. Add acid till the cell is nearly full; note whether the deflection changes.

Now substitute carbon and zinc for the copper and zinc, and see if the deflection is the same: then add chromic acid, and again note the deflection.

102. If the resistance of the galvanometer is high enough, your experiment will show that the current which a cell will send through it does *not* depend appreciably on the internal resistance of the cell (p. 68), but does depend on the materials of which the cell is made. If, however, the resistance of the galvanometer is not high enough (as was the case in Experiment 46), a change in the resistance of the cell will appreciably alter the total resistance through which the cell has to drive the current, so that though the cell may have the same *tendency* to produce a current, yet the conditions differ sufficiently to cause the current to change.

If the total resistance is very large, a change in that of the cell will not appreciably affect it, and the conditions for each of the cells are practically the same, then we see that the *tendency* of a cell to produce a current varies with the materials of which it is made.

To this tendency a name is given, **Electromotive force**, and it may be defined thus: *Electromotive force is that which produces, or tends to produce, movement of electricity.*

The student must clearly recognize that it is not a force in the ordinary sense, since by definition 'Force is that which produces or tends to produce motion in *matter*.' Nor must he look on it as being like the magnetic forces dealt with in Part I, since these tend to move

the matter of the magnet, or even exactly like the electric forces between two charged bodies, dealt with in Part III, since in that case also the lines of force tend to move the charged bodies themselves, and not only the electricity in them *.

'Electromotive force' is commonly abbreviated into E.M.F.

103. Unit for E.M.F. We have seen in Experiment 56 that the E.M.F. of a cell depends on the material of the cell; we now require a standard or unit with which to compare the E.M.F. of various cells.

The most natural thing to do is to take some cell, which can easily be set up, as having unit E.M.F. But there is a certain E.M.F. which depends on the fundamental units, the centimetre, the gramme, and the second, together with the magnetic action of a current of electricity, and it is most convenient to take this, or some simple multiple of it, as the unit of E.M.F. The name given to the **practical** unit of E.M.F. is the **Volt**, in honour of Volta.

Unfortunately, no cell has exactly this theoretical E.M.F.; but by careful experiments it has been found that a certain cell, called Latimer Clark's standard (see p. 65), if made up according to a certain specification and measured at a temp. of 15° C. has an E.M.F. equal to 1·434 of these theoretical volts, and a Weston cell an E.M.F. of 1·0183 volts.

Either of these cells, then, can be used as a standard just as conveniently as if it had an E.M.F. of 1 volt; other cells can be compared with it, and their E.M.F. calculated.

The advantage of the standard cell is the uniformity of its E.M.F. when made with pure materials, and the fact that it does not alter with age; its disadvantage is that its internal resistance is large, and that no moderately large current can be taken from it.

104. Comparison of E.M.F. by a galvanometer. The E.M.F. of two cells can be numerically compared by direct comparison of the currents which they can produce through the same very large resistance. This latter must be large enough to render negligible the resistances of the cells themselves, so that the total resistances through which the cells have to drive the currents are sensibly the same; we do not know the value in ohms of the internal resistances of these

* The ideas of Electromotive Force and Current may be made clearer by their analogy to the hydrostatic pressure of water in a pipe and the current of water which would flow out if the tap were opened. In this case it is the pressure which produces or tends to produce movement of water.

cells, but if both are negligible in comparison with the total resistance in circuit, the conditions are equal.

Since the currents will be small, a sensitive galvanometer will be needed to compare them; and since a numerical comparison is required, either a moving coil galvanometer, or a tangent galvanometer, or a mirror galvanometer must be used.

The first or last can be used in series with a separate high resistance, from 5,000 to 50,000 ohms as required; the tangent galvanometer will need a large number of turns of fine wire in its coil to give it the necessary sensitiveness, and hence it may offer sufficient resistance without any addition.

The E.M.F. of the cells will then be directly proportional to the currents, and if the E.M.F. of one cell is known, that of the other can be calculated.

M. EXPERIMENT 57*a*. **To compare E.M.F. of two cells by a moving coil galvanometer, or mirror galvanometer.** Connect in series a cell, the galvanometer, and one or two resistance boxes, with say 40,000 ohms in circuit. Reduce this resistance until the deflection of the galvanometer is about half-way across the scale; note this deflection.

Substitute other cells, without altering the resistance found suitable in the first case, and tabulate the deflections for the different cells.

We do not require to know the value of the resistance in circuit, or the current in amperes in each case, but we know that these currents are proportional to the observed deflections, so that the E.M.F.'s of the various cells are proportional to the deflections.

If one of the cells is a Clark cell, the deflection it gives represents 1·434 volts; if this deflection is m scale divisions, 1 scale division corresponds to $\frac{1·434}{m}$ volts, and hence the E.M.F. of each of the other cells can be determined in volts. Compare the values so obtained with the table on p. 66.

T. EXPERIMENT 57*b*. **To compare the E.M.F. of two cells by a high resistance tangent galvanometer.** Observe the currents produced through the tangent galvanometer by cells of various types, and tabulate the results. It is not necessary to find the values of the currents in amperes, but merely to find numbers proportional to each current, i.e. the corresponding tangent of the angle of deflection for the tangent galvanometer, or the number of scale divisions for the mirror galvanometer.

If one of the cells so tested is a Daniell cell made up with sulphuric acid, its E.M.F. may be taken as 1·1 volt; or if a fairly fully charged accumulator is available, its E.M.F. may be taken as 2·0 volts, though neither of these values is comparable for accuracy with the 1·434 volts of a Clark cell. The Clark cell cannot be used satisfactorily with less than about 10,000 ohms in circuit with it, and the current through such a resistance would probably be too small to be measured by a tangent galvanometer.

Hence calculate the E.M.F. of all the cells you can test, and compare them with the table on p. 66.

105. Voltmeters. A voltmeter * usually consists of a sensitive galvanometer with a coil of high resistance in series with it in the same case, the scale being marked to show directly in volts the E.M.F. of any cell attached to its terminals. The resistance for a voltmeter registering up to about three volts, which is a convenient range for a laboratory instrument, need not be more than about 50 to 150 ohms, though the higher it is the better; but one adapted to measure the E.M.F. maintained on the mains of an electric light supply must be much higher, about 5,000 ohms.

T. EXPERIMENT 58. Test the E.M.F. of as many cells as you can (except a Clark's cell) with a voltmeter, and compare the results with those got by a tangent galvanometer in Experiment 57 *b*.

If you can trust the accuracy of your voltmeter, a comparison of the results for any one cell will enable you to calculate the 'constant' of the high resistance coil of your tangent galvanometer considered as a voltmeter, i.e. the number by which you must multiply the tangent of the angle of deflection of the needle in order to find the number of volts in the E.M.F. of a cell or battery connected to the terminals of the coil.

Find this constant.

M. EXPERIMENT 58 *a*. **To calibrate a moving coil galvanometer and a high resistance for use as a voltmeter.** Let us suppose that the scale has 30 divisions, and that we want the voltmeter to read up to 3 volts. Then each division represents ·1 volt, and a Clark cell should produce a deflection of 14·3 divisions.

Connect in series with the galvanometer two or three resistance boxes, and a Clark cell, and reduce the resistance until the deflection

* Not to be confused with voltameter.

is 14·3 divisions. The galvanometer and this resistance then form the required voltmeter.

Measure with it the E.M.F. of one or two other cells, and check by a standard voltmeter.

106. Cells in series and parallel. EXPERIMENT 59. Take two similar cells, such as two Leclanché, or two Daniell cells. By means of a voltmeter or, failing that, of a high-resistance tangent galvanometer, determine the E.M.F. of each, which should be nearly the same for the purpose of this experiment.

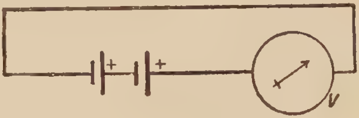


Fig. 63. Cells in Series.

Now connect them 'in series' as described on p. 86, and test the E.M.F. of the combination, as arranged in Fig. 63, where *V* is the voltmeter.

Is it the sum of the separate E.M.F.?

Next connect the two + poles together and the two – poles together, and treat them as the + and – poles of a cell; this method of connecting the cells is called 'in parallel.'

Determine the E.M.F. of the combination, as shown in Fig. 64.

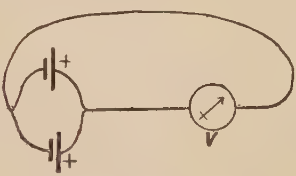


Fig. 64. Cells in Parallel.

Two or more similar cells connected in parallel are clearly only equivalent to one cell whose plates are of larger size, so that from Experiment 56 we should not expect the E.M.F. to differ from that of a single cell. The only advantage in using either a larger cell or several connected in parallel is that the internal resistance is less, so that a larger current will flow from it through a *small* external resistance; and if the same current be taken from it, the current will flow for a longer time without exhausting the materials.

Cells of different kinds should never be connected in parallel, though they may be connected in series.

106 a. Potential Difference. We have considered the 'tendency' of a cell or battery to send a current, but we are more

concerned with what happens when it succeeds in doing so. Suppose a battery (*E* in Fig. 64 *a*) causes a current to flow round a circuit *ABCD*; this current is opposed by resistances all along its path, so the E.M.F. of the battery causes electric forces in each of these resistances. To maintain the current in each several part, *AB*, *BC*, *CD*, accounts for a corresponding fraction of the E.M.F. of the battery, depending on the resistance of that part. It is usual to term the fraction of the E.M.F. of the battery which is devoted to producing the current in *BC*, 'the *Potential Difference* between *B* and *C*.' This is usually written P.D.

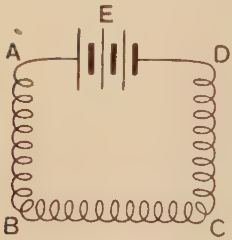


Fig. 64 *a*.

As this P.D. is in the nature of E.M.F., it is expressed in volts, and can be measured in the same way as E.M.F., i.e. by connecting the terminals of a voltmeter (or high resistance galvanometer) to *B* and *C*, as in Fig. 64 *b*.

Some current then flows through the voltmeter, as in measuring the E.M.F. of a cell, and so to some extent alters the P.D. between *B* and *C*; but the amount of this current, and therefore the error produced by the voltmeter, is negligible if the resistance of the voltmeter is high compared with that of *BC*.*

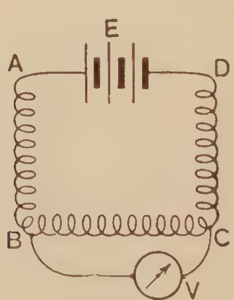


Fig. 64 *b*.

Although P.D. is expressed in the same units as E.M.F. and measured by the same instruments, there is, strictly speaking, a difference between them which cannot be made clear at this stage.

* For further explanations on this point, see p. 107.

But the distinction must be observed, that E.M.F. is used only when we speak of the cause of an electric current (whether in a battery, dynamo, &c.) without regard to the current which happens to be flowing, whereas P.D. can be used when we are dealing with the parts through which a current is being urged, as well as with the parts where the 'driving force' is situated.

C.G.S. Electro-magnetic Units.

107*. Current. We have seen in Chapter VII that if we define our unit of current by the rate at which it deposits a metal, the magnetic field at the centre of a circular conductor carrying a current is proportional to the current and inversely proportional to the radius of the circle.

Instead of starting with the above definition of the unit and experimenting on the field of force produced, we might have defined the unit current as that capable of producing at the centre of a given coil a certain magnetic field; by the application of mathematical reasoning we could then arrive at the reduction factor of a tangent galvanometer given on p. 90, and experiment would then give the metal-depositing power of a current as measured on this principle.

This is the basis of the theoretical electro-magnetic units. On p. 26 was given the definition of a unit magnetic pole as being of such a magnitude that at 1 cm. from a similar pole it would repel it with a force of 1 dyne.

Imagine such a unit-pole to be situated at the centre of a circular conducting ring 1 cm. in radius, and suppose a current to be flowing along an arc of this circle 1 cm. in length, then if the unit-pole is urged outwards with a force of 1 dyne the current has a strength of 1 *electro-magnetic unit*.

If this current flows completely round the circular conductor, which is of length 2π cm., it is reasonable to suppose that the magnetic force on a unit-pole at the centre will be 2π dynes instead of 1 dyne; if there are n turns instead of one, that it will be $2\pi n$ dynes; and it can be shown experimentally that the magnetic force on unit-pole, at the centre of a circular wire, varies inversely with the radius, so that we arrive at the result that the magnetic force on a unit-pole, at the centre of a circular coil of n turns each of radius r cm. in which a current of C electro-magnetic units is flowing, is

$$\frac{2\pi n C}{r} \text{ dynes.}$$

(Compare the formula on p. 90.)

Quantity. On this system of units the unit quantity of electricity is that conveyed by unit current in 1 sec.

P.D. Two points on a conductor are said to have unit P.D. between them, when it requires the expenditure of unit quantity of work (1 erg) to force unit quantity of electricity from one point to the other along the conductor.

Resistance. The unit of resistance is based on those of current and P.D.;

a conductor is said to have unit resistance when unit current is maintained by unit P.D. between the ends of the conductor.

108*. This system of units is theoretically excellent, as it is based directly on the centimetre gramme and second, and the fundamental properties of magnet-poles and electric currents (hence they are called C.G.S. units), while the 'practical' units as defined in Chapters V, VI, and VIII are apparently perfectly arbitrary. The latter are, however, of a convenient magnitude, and, as we have seen, the measurement of quantities in terms of them is a simple matter, while direct measurement in terms of the C.G.S. units involves immense labour. The practical units are based on the C.G.S. units as follows:

The ampere = $\frac{1}{10}$, or 10^{-1} C.G.S. units of current.
The ohm = 1000000000, or 10^9 C.G.S. units of resistance.
The volt = 100000000, or 10^8 C.G.S. units of E.M.F.

The values of the ampere, ohm, and volt given on pp. 73, 69, 98, which best represent the above theoretical values, were deduced from a large number of careful experiments and were fixed by the International Conference of 1908.

It will be seen that the practical and C.G.S. systems alike give such numerical magnitudes to the quantities involved, that the expression for Ohm's law, $C = \dfrac{E}{R}$ is true, no numerical coefficient being needed for $\dfrac{E}{R}$.

It may also now be clear why the constant for the tangent galvanometer was stated on p. 90 to be $\dfrac{2\pi}{10}$ instead of ·6283, or $\dfrac{\pi}{5}$; since for measuring currents in C.G.S. units the constant would be 2π, and the reduction factor $\dfrac{Hr}{2\pi n}$, and it is convenient to keep the form the same, the presence or absence of the 10 showing whether it refers to practical or C.G.S. units. This is a matter in which confusion often arises.

109*. Comparison between electrostatic and electro-magnetic units. A similar C.G.S. system of electrical units is explained on pp. 243, 265 for static electricity, and care must be taken not to confuse the units. Although both are based on the centimetre, gramme, and second, similar units do not have the same magnitude. For example, the electro-magnetic unit of quantity represents an amount of electricity 3×10^{10} times as large as the electrostatic absolute unit. This number is the speed of light in cm. per sec., and the fact that it, or some power of it, represents the connection between the magnitudes of all corresponding units on the two systems is of very great importance, as supporting the theory as to the electro-magnetic nature of light.

CHAPTER IX

Ohm's Law

110. There must be a law connecting the resistance of a conductor, the P.D. between its ends, and the current flowing in it; we will now find it. The law was discovered by G. S. Ohm, and is called Ohm's Law.

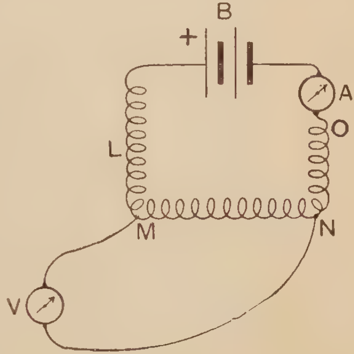


Fig. 65 *a*.

Experiment 60. Take a constant cell, or battery of two or three cells (*B*, Fig. 65 *a*); connect it in series with a resistance and an ammeter or tangent galvanometer. If a set of known resistances, capable of safely carrying a current of one or two amperes, is available, an ammeter is most convenient (as in Fig. 65 *a*, where *A* is the ammeter and *LM*, *MN*, *NO* are the resistances each of one or two ohms); if the resistance-box will not safely carry a fairly large

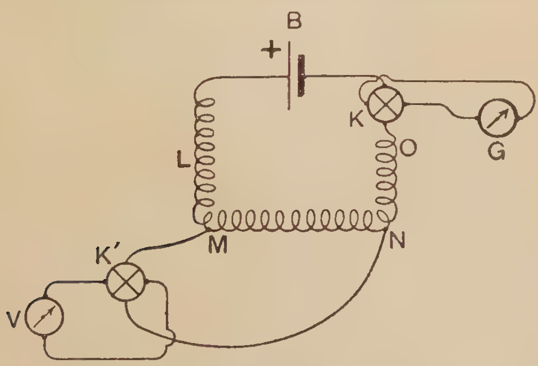


Fig. 65 *b*.

current, the best arrangement is shown in Fig. 65 *b*, where *G* is a tangent galvanometer, connected with the circuit by means of

a commutator K. The 'deflection of the galvanometer' then means the average of four readings of the end of the pointer; the resistances $L\,M$, $M\,N$, $N\,O$ represent coils in the resistance-box.

Now take a voltmeter, or high resistance tangent galvanometer *, V. Connect its terminals to the ends of each of the resistances in succession, while the current flows round the circuit. The readings of the voltmeter, or the tangent of the angles of deflection of the high resistance galvanometer, measure the P.D. between the ends of the respective resistances while the same current flows through each resistance. Enter the corresponding values in a table.

Connection between P.D. and R (current constant).		
P.D.	Resistance in ohms.	

For use in the second part of the experiment, observe and record the value of the current as shown by A or G.

Can you perceive any simple connection between the resistance and the P.D. between its ends? For example, is the P.D. directly proportional to the resistance, inversely proportional to it, or directly proportional to the square of the resistance? In the first case, $\frac{\text{P.D.}}{\text{resistance}}$ would be about the same for each resistance; in the second, P.D. $\times$ resistance; in the third $\frac{\text{P.D.}}{(\text{resistance})^2}$.

When you have determined what is the connection, put in the second line of the third column the expression

$$\left(\frac{\text{P.D.}}{\text{resistance}},\ \text{P.D.} \times \text{resistance, \&c.}\right),$$

which has a constant value, and below it put the actual value of this expression in each case.

Next keep V connected to the ends of one resistance, say $M\,N$, and alter the current in the circuit. This can be done by altering the number of cells in B, or by changing the resistances $L\,M$, $N\,O$, &c. (not $M\,N$), in the circuit. Observe the current in each case by

* If the latter is used, it is best to connect it through a commutator K' as in Fig. 65 *b*, and take the average of four readings as usual.

reading A or G, and observe the corresponding values of the P.D. at the ends of $M\ N$ by reading V. Enter the results, including the one got in the first part of the experiment, in a table as follows :—

Connection between P.D. and Current (Resistance constant).		
P.D.	Current.	

Determine as before the law connecting P.D. and current for a given resistance, and fill up the third column.

111. Experiments such as No. 60 show that the P.D. between the ends of a resistance through which a current is flowing is directly proportional to the resistance if the current is unchanged; and that the P.D. between the ends of a conductor is directly proportional to the current flowing in it if the resistance of the conductor is unchanged.

The first statement means that if the resistance is multiplied by any factor, the P.D. will be multiplied by the same factor; the second, that if the current is multiplied by any factor, the P.D. will be multiplied by the same factor. These two can be combined into one statement, that *the P.D. is directly proportional to the product of the current and resistance*; for if either of the latter is multiplied by any factor, so is their product.

If the resistance of the conductor is R, the current in it C and the P.D. between its ends V, Ohm's law may be expressed as $V = K\,C\,R$, where K is a number, which does not vary with V, C, or R.

112. We have not yet taken into consideration the units in which V, C, and R are measured, so that the value of K has not been determined in our experiments.

E.M.F. and P.D. are measured in *volts*, each of which is $\frac{1}{1{\cdot}434}$ of the E.M.F. of a Clark cell; currents are measured in *amperes*, an ampere being the current which will deposit silver at the rate of ·001118 grm. per sec.; and resistance is measured in *ohms*, an ohm being the resistance of a standard piece of wire.

These units were originally fixed so that the value of K should be unity; i.e. they are of such magnitudes that when a P.D. of 1 volt is

maintained between the terminals of a 1 ohm coil, the current in it is 1 ampere. Any two can be fixed arbitrarily, and the value of the third must then be taken which will make $K = 1$.

Hence Ohm's law may be stated, for a conductor which does not contain a battery or other source of E.M.F., as follows :—'*The P.D.* (*in volts*) *between the ends of a conductor is equal to the product of the current* (*in amperes*) *into the resistance* (*in ohms*)'; or in symbols, $V = C R$, or $C = \frac{V}{R}$.

A method of verifying this law will serve as an introduction to the accurate methods of measuring E.M.F. (or P.D.) and resistance, invented respectively by Poggendorf and Wheatstone.

EXPERIMENT 61. An instrument called a Potentiometer will be required *, consisting essentially of a thin uniform uncovered wire of high resistance, such as platinoid, stretched along a scale, furnished with some means of making electrical contact at any point of the wire.

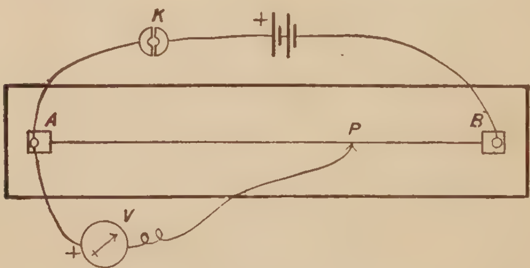


Fig. 66.

Through this wire a constant current must be maintained, e.g. by a battery of three Daniell cells in series, or two accumulators.

The connections are made as in Fig. 76, where the potentiometer wire is represented by $A B$, P being the contact-maker. V is a galvanometer, graduated to serve as a voltmeter, with a resistance very much larger than that of $A B$.

K is a key for breaking the circuit, except while a reading is actually being made, in order that the constancy of the battery may be preserved.

* A B.A. wire bridge will serve, though the wire of this has usually a low resistance, so that it may be difficult to maintain the required E.M.F. between its ends.

Make contact with the wire *A B* at *P* and note the length *A P* and the P.D. between *A* and *P* as shown by the voltmeter.

Repeat this for different positions of *P* along *A B*.

The resistance of *A P* will be proportional to the length, since the wire is uniform, so that by Ohm's law the quotient of the observed P.D. divided by this length should be a constant number.

Tabulate your results as follows:—

Length *A. P.*	P.D. between *A* and *P*.	$\frac{\text{P.D.}}{\text{Length.}}$

Are the numbers in the last column the same? If so, it shows that the 'P.D. per cm.' along the wire is constant.

113. Measurement of resistance by ammeter and voltmeter. If a known current passes through a resistance, and the P.D. between the terminals of the resistance is measured, the value of the resistance can be deduced by Ohm's law.

For if the observed P.D. be V volts, and the observed current be C amperes, and if R ohms be the value of the resistance, then $V = CR$, or $R = \frac{V}{C}$.

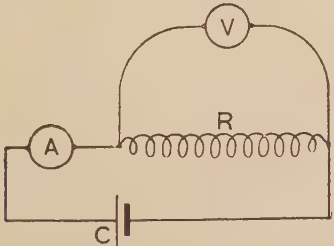


Fig. 67.

This method is convenient for measuring a small resistance which is capable of carrying a considerable current, such as the armature of a dynamo; its accuracy depends on the accuracy and sensitiveness of the voltmeters and ammeters which are available.

EXPERIMENT 62. If a voltmeter reading to 3 volts, and an

ammeter reading to 1 ampere, are available, you can use them to find the resistance of a length of platinoid wire, as follows. Take a metre of No. 26 platinoid wire, represented by *R* in Fig. 67, and connect up the ammeter *A*, voltmeter *V*, and a single storage cell *C*, as shown.

Read *A* and *V*, and deduce *R* by Ohm's law.

Similarly measure the resistance of a 16 c.-p. carbon-filament lamp when hot, using a suitable ammeter and voltmeter as in

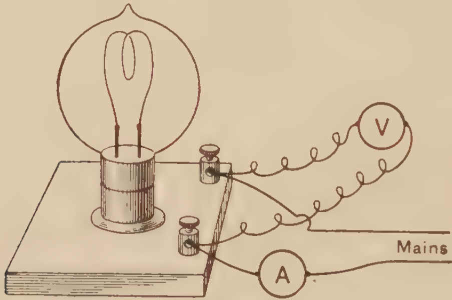


Fig. 68.

Fig. 68. The voltmeter must be constructed to read up to the full 'voltage' of the mains, but the ammeter need only read up to about 1 ampere.

If now the resistance of the same lamp be measured when cold by the method of Art. 75 (or preferably by that of Art. 125 or 126), a difference will be observed, as noted in Art. 131. If a metal-filament lamp be used, the difference will be the other way.

If you have cells capable of furnishing a large current, such as 25 amps., and a suitable ammeter, you can in this way measure the resistance of a yard of No. 18 copper wire, whose resistance is about $\frac{1}{80}$ ohm.

It should be noted that this method has an advantage over others in that we can determine the resistance of the conductor when actually carrying the current it is intended to carry; for example, we can observe the changing resistance of the field-coils of a dynamo or motor as they heat up while the machine is in continuous use. On the other hand, with voltmeters and ammeters as ordinarily graduated, it is not possible to determine the value of a resistance to the same degree of accuracy as by the method of Art. 125.

114. Measurement of current by a voltmeter and a known resistance. If an unknown current passes through a known resistance, and the P.D. between the terminals of the resistance is measured, the value of the current can be deduced by Ohm's law.

For if the observed P.D. be V volts, and the resistance be R ohms (Fig. 69), and if C amperes be the (unknown) current, then $C = \frac{V}{R}$.

This method of measuring currents is very commonly used, especially where the currents are large, needing heavy conductors to carry them. For with this method it is not necessary to pass large currents through a delicate instrument; and the instrument to be observed (the voltmeter) can be fixed at some distance from the 'main' carrying the current to be measured, since it can be connected to the ends of the known resistance, which forms part of the main, by wires which may be long and thin without introducing errors into the result.

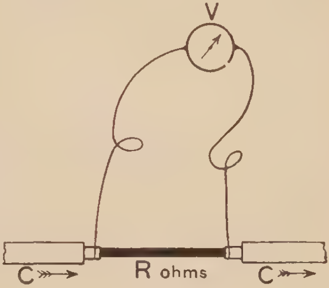


Fig. 69.

For example, if the voltmeter is joined to the ends of a section of the conductor whose resistance is known to be ·1 ohm, and the voltmeter shows 5·3 volts. the current in that section of the conductor is $\frac{5{\cdot}3}{{\cdot}1}$, or 53, amps.

The current in the conductor on each side of the section will be slightly greater, by the amount that flows through the voltmeter, but if the resistance of the voltmeter is large, this current will be negligible; or it may be calculated and allowed for by a method to be described in Art. 117.

115. Resistances in parallel. When two or more wires are connected together at their ends, so that the current divides and part flows through each, they are said to be 'in parallel.'

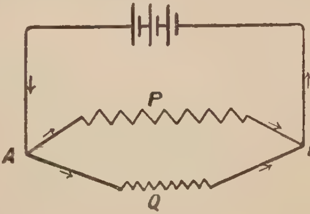


Fig. 70.

Consider the circuit represented in Fig. 70, where APB, AQB are two resistances in parallel.

Suppose that the resistances of these are respectively R_1 and R_2 ohms; let us call the currents through these C_1 and C_2 amperes, and the P.D. between A and B, V volts.

Then Ohm's law applied separately to the wires APB and AQB gives

$$C_1 = \frac{V}{R_1}, \text{ and } C_2 = \frac{V}{R_2} \quad \dots \dots \dots \quad \text{(i)}$$

Therefore the total current furnished by the battery (call it C amperes) is

$$C = C_1 + C_2 = V\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \quad \dots \dots \dots \quad \text{(ii)}$$

$$= V \cdot \frac{R_1 + R_2}{R_1 R_2}.$$

Hence $$V = C \cdot \frac{R_1 R_2}{R_1 + R_2}$$

and from (i) $$C_1 = C \cdot \frac{R_1 R_2}{R_1 + R_2} \cdot \frac{1}{R_1}$$

$$= C \cdot \frac{R_2}{R_1 + R_2}. \quad \dots \dots \dots \quad \text{(iii)}$$

Similarly $$C_2 = C \frac{R_1}{R_1 + R_2}.$$

Thus we have found the fractions into which the main current divides itself in passing through two resistances in parallel.

Again, Ohm's law states that if a current of C amperes flows through a single resistance of R ohms, and there is a P.D. of V volts between its ends, then

$$C = \frac{V}{R} = V \times \frac{1}{R}.$$

Comparing this with (ii), we see that a single resistance of R ohms is equivalent to these two resistances, R_1, R_2 ohms in parallel, provided that

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}.$$

The same reasoning will hold whatever the number of resistances in parallel; so that we have: *the reciprocal of the resistance equivalent to a number of conductors in parallel is equal to the sum of the reciprocals of their separate resistances.* Since the *conductance* may be defined as the reciprocal of the resistance, this may be better stated as: *the conductance of a number of conductors in parallel is the sum of their separate conductances.*

116. Shunts. If it be desired to reduce the sensitiveness of an instrument such as a galvanometer, a **shunt** may be used, consisting of a wire connected in parallel with the instrument.

Thus if G (Fig. 71) be a galvanometer connected to a commutator K, and R a resistance in parallel with the galvanometer, then only a fraction of the current flowing through K will pass through G. The value of this fraction can be calculated if the resistances of R and G are known; frequently, however, this is not required, and a convenient unmeasured resistance is used to shunt G.

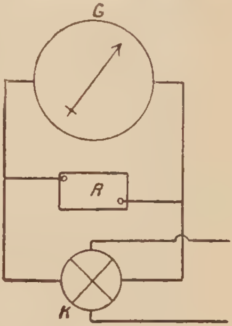


Fig. 71.

If the current through K is to be calculated from the galvanometer reading, the relation between the two resistances in parallel must be known. Suppose the resistance of the galvanometer is G ohms and of the shunt R ohms. Then by Art. 115, if C be the total current through K, the amount passing through the galvanometer will be

$$\frac{R}{G+R} \times C.$$

It is usual to make R either $\frac{1}{9}, \frac{1}{99}$, or $\frac{1}{999}$ of G; this will simplify the above value. Suppose $R = \frac{1}{99} \times G$, then the current through the galvanometer will be

$$\frac{\frac{G}{99}}{G+\frac{G}{99}} \times C \quad \text{or} \quad \frac{1}{100} C.$$

More generally, if the shunt has $\frac{1}{n}$ of the galvanometer resistance, $\frac{1}{n+1}$ of the current will flow through the galvanometer.

M. 117. Moving coil ammeter. We can now see how the galvanometer in Article 114 can have its scale marked, so that it may indicate the amperes in the conductor before the current reaches the known resistance. For suppose that the total resistance of the galvanometer used as voltmeter, the resistance in series with it, and its leads is R ohms, and that of the resistance interposed in the mains is r ohms,

and call the current to be measured C amperes, and the current through the galvanometer C_g amperes. Then by (iii) of Article 115 we have

$$C_g = C \cdot \frac{r}{R+r},$$

or

$$C = C_g \frac{R+r}{r}.$$

So if the galvanometer tells us the current flowing through it, we can directly deduce the total current in the mains by multiplying the former by $\frac{R+r}{r}$; and the scale of the galvanometer can of course be graduated to show the current in the mains instead of that passing through the galvanometer.

Such an instrument is called a Moving Coil Ammeter, and ammeters are very commonly made on this principle.

For example, suppose that the galvanometer, of resistance 6·2 ohms, is such that a current of ·1 ampere deflects the pointer the full length of the scale of 100 divisions (these being all of equal value), and that the resistance of the shunt is ·1 ohm; what is the value of a division of this instrument regarded as an ammeter? We have 1 division deflection for ·001 amp. through the galvanometer, or for $\cdot 001 \times \frac{6 \cdot 2 + \cdot 1}{\cdot 1}$ amps. through the mains.

So 1 division = ·063 amp., and the largest current the instrument will measure is 6·3 amps.

Note that in this case 6·2 amps. flows through the shunt, and ·1 amp. through the galvanometer.

If we are provided with a set of suitable shunts we can use the one galvanometer for a very wide range of currents. For suppose that the galvanometer, of resistance R ohms, is such that a current of c amps. deflects it 1 division. Then as before, with a shunt of resistance r ohms one division indicates $c \cdot \frac{R+r}{r}$ amps. through the mains. By suitably selecting the resistance, r, of each of these shunts, we can make this quantity $c \cdot \frac{R+r}{r}$ what we please; say ·01, ·1, 1, 10, &c., amps., in which case if the galvanometer has say 100 divisions it will measure currents up to 1 amp. by hundredths of an ampere, those up to 10 amps. by tenths, and so on, by using the appropriate shunt. If, for example, the galvanometer resistance is 6·2 ohms, and $c = \cdot 001$ amp. as before, the resistances of these shunts must be respectively ·69, ·0626, ·00621, &c., ohms approximately.

The value of c can conveniently be found for a sensitive galvanometer by applying Ohm's Law to the circuit formed of the galvanometer, a resistance of say 40,000 ohms, and a Clark's cell.

EXPERIMENT 63. **Moving-coil Ammeter.** Assuming that you have a sensitive moving-coil galvanometer, recording thousandths of an ampere, it is required to prepare a shunt for it so that it will record amperes in the main circuit, one scale division having some assigned value in amperes. Let the resistance of the galvanometer be R ohms; if this is not known, it must be found by the method of Experiments 48, 68, or 69 (the coil must be fixed meanwhile).

Connect up about 40,000 ohms, a Clark's cell, the galvanometer, and a key in series Alter the resistance so that the galvanometer deflection is, say, 20 divisions. Calculate by Ohm's Law the current through the circuit (though the resistance of the cell is small compared with the total resistance in circuit, some reasonable amount, such as 100 ohms, should be ascribed to it); hence find the value in amperes (c) of one scale division of the galvanometer.

Calculate the resistance (r ohms) of a shunt which will make the quantity $c\dfrac{R+r}{r}$ whatever is required to be the value of one scale division, in amperes in the main circuit; take a length of wire of this resistance and put it in parallel with the galvanometer.

In Art. 110 we assumed that all the current measured by A also passed through the resistance MN. This was not strictly correct, as some would flow through V; if C amps. be the current recorded by A, and r ohms be the resistance of MN, and R ohms the resistance of V, then the current through MN is (see Art. 115) $\dfrac{R}{R+r} \times C$ amps. Writing this in the form $\dfrac{1}{1+\dfrac{r}{R}} \times C$ amps., it is clear that this current through MN is less than C, but that the difference is small if $\dfrac{r}{R}$ is small. Hence the actual P.D. between M and N (which we measure by the voltmeter) is not quite so large as that which would be needed to drive the current C through MN. But we can make this error very small by using a voltmeter whose resistance (R) is very large compared with that (r) of MN.

118. Ohm's Law for a complete circuit. Suppose that we have a closed circuit as in Fig. 72, consisting of a battery or other source of current, of E.M.F. E volts, and internal resistance B ohms, a resistance of R ohms, and a galvanometer or ammeter of resistance G ohms, all connected in series. The meaning of the 'internal resistance of a battery' has been suggested in Art. 68; the E.M.F. of the battery is the P.D. between its terminals when no current is flowing through it. The latter we can measure, either

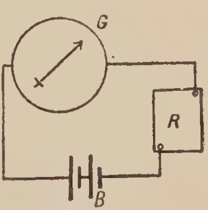


Fig. 72.

by an electrostatic voltmeter or a potentiometer (see Art. 123) which takes no current, or a galvanometer of very high resistance which takes very little. The internal resistance of the cell, which we have called B ohms, cannot be determined by the methods used for a wire.

But we may think of a cell as consisting of a single source of E.M.F. whose value does not change (except from polarization) whatever current flows through it, and which offers no resistance, together with an actual resistance measurable in ohms. It is not an accurate representation, but it helps to clear ideas. So that the cell is to be thought of as Fig. 72 *a*, where E is the source of E.M.F., and B the resistance. Our circuit then becomes as in Fig. 72 *b*. If we apply Ohm's Law to

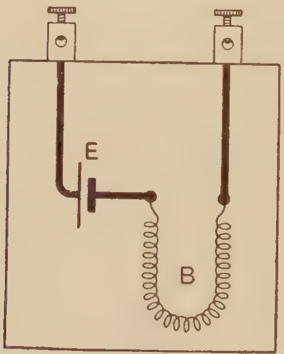


Fig. 72 *a*.

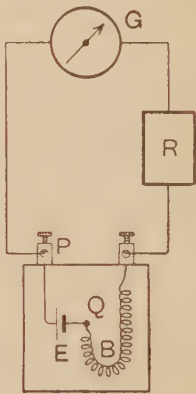


Fig. 72 *b*.

the resistances B, R, and G, taking the P.D. between P and Q as being E volts, and measuring the current produced, we get a value for B in ohms; if we repeat this for different values of R, *it will be found that* we get approximately the same value for B in each case. This is more accurately true when the armature of a dynamo is the source of E.M.F.; the law then applies strictly, if we give to B the actual resistance of the armature, as determined when it is at rest and no longer a source of E.M.F.

So (with this meaning attached to 'resistance of a battery') we can apply Ohm's Law to a complete circuit, in the form, *The current (in amperes) flowing round a circuit is found by dividing the E.M.F. (in volts) by the total resistance (in ohms).*

Thus if E volts be the E.M.F. of a battery, and B ohms its internal

resistance, and if R be the resistance of the remainder of the circuit, and if the current flowing in the circuit be C amperes, these quantities are connected by the relation

$$C = \frac{E}{B+R}.$$

119. Internal Resistance of a Battery. In order to make clearer the meaning of internal resistance of a battery, as above defined, suppose we have a cell whose E.M.F. is found to be 1·45 volts (by the use of a voltmeter or potentiometer); and suppose that when coupled to an ammeter whose resistance is 2 ohms it is found to give a current of ·58 amp. Calling the internal resistance of the cell B ohms, we have by the above relation

$$\cdot 58 = \frac{1{\cdot}45}{2+B}; \text{ hence } 2+B = \frac{1{\cdot}45}{\cdot 58} = 2{\cdot}5, \text{ and } B = \cdot 5 \text{ ohm.}$$

This gives a value for the internal resistance which we may use in applying Ohm's Law to another circuit containing this cell, in order to predict the current which will flow. For example, suppose that the cell is coupled to a circuit whose total resistance, apart from that of the cell, is 7 ohms, we can expect a current of

$$\frac{1{\cdot}45}{7+\cdot 5}, \text{ or } \frac{1{\cdot}45}{7{\cdot}5}, \text{ or } \cdot 194 \text{ amp.}$$

EXPERIMENT 64. **To measure the internal resistance of a battery.**

M. (1) If an ammeter and voltmeter are available. First find the resistance of the ammeter, by the method of Experiment 48 or otherwise; call it G ohms. Find the E.M.F. of the battery by means of a high-resistance voltmeter; call it E volts. Connect in series the battery, the ammeter, and sufficient resistances of known value (adapted to carry the greatest current for which the ammeter is graduated) to give a deflection within the scale of the ammeter; call the resistance R. Observe the current shown by the ammeter; call it C amps.

Then $$C = \frac{E}{B+G+R};$$

hence $$B+G+R = \frac{E}{C}, \text{ and } B = \frac{E}{C} - G - R.$$

T. (2) If only a tangent galvanometer is to be used, arrange the battery whose resistance is to be measured (which may con-

veniently consist of two or three Daniell cells in series), a resistance-box, a commutator, and a tangent galvanometer. The resistance of the galvanometer must be known, or measured by some method such as that of Experiment 48.

A resistance (R ohms) must be taken out, of such a magnitude as to bring the deflection of the galvanometer between 40° and 70° ; it simplifies the work if there is no need to introduce a resistance.

Take the galvanometer deflection ($\delta°$ say); find, from the tables, the value of $\tan \delta°$; then the value of the current is $K \times \tan \delta°$, where K is some number which we do not need to know.

Take out plugs from the resistance-box until the deflection is between 20° and 30°; call the total resistance of the box now effective R' ohms; take the new deflection (δ' say): then the new current is $K \tan \delta'$.

Then by Ohm's Law we have, if E volts be the E.M.F. of the battery (which we shall not need to know), B ohms its resistance (which we have to find), and G ohms the resistance of the galvanometer,

$$E = K \tan \delta \, (B+G+R) \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and

$$E = K \tan \delta' \, (B+G+R') \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Hence $\quad \tan \delta \, (B+G+R) = \tan \delta' \, (B+G+R')$,

since each is equal to $\dfrac{E}{K}$.

From this the value of B can be found, if the value of G is known.

In order to obtain an accurate result, it is essential that $R+G$ be small compared to B, or a small error will give a large percentage error for B, and may even produce a negative value. If the tangent galvanometer is too sensitive, so as to demand a large resistance in the circuit, it may with great advantage be 'shunted' (p. 105) by connecting its terminals by a piece of platinoid wire as an alternative path for the current. Care must, however, be taken that this does not draw so large a current from the battery as to damage the resistance-box or battery, or to polarize the battery, since we assume that its E.M.F. is unchanged throughout.

To make clearer the meaning of total resistance, E.M.F., &c., the following examples may be useful.

EXAMPLE I. Consider a circuit composed of a series of 4 chromic acid cells and a glow-lamp with a filament of carbon. Suppose the E.M.F. of each cell

to be 2 volts, and the resistance of each to be ·25 of an ohm; and let the resistance of the glow-lamp be 3 ohms. Then the E.M.F. of the battery is 4×2, or 8 volts; its resistance is $4 \times \cdot 25$, or 1 ohm; so that the total resistance of the circuit is $1 + 3$, or 4 ohms. The current flowing through the lamp is then

$$\frac{8}{4}, \text{ or } 2 \text{ amperes.}$$

This lamp would then give a light of about 3 'candle-power.' If the filament had been of metal, it would have given about 10 candle-power.

EXAMPLE II. Suppose that a circuit consists of a battery of three Leclanché cells in series, each of E.M.F. 1·45 volts and of internal resistance ·5 ohm, of a galvanometer of resistance 2 ohms, and a wire of resistance 150 ohms, the current flowing in the circuit will be

$$\frac{3 \times 1{\cdot}45}{3 \times {\cdot}5 + 2 + 150} \text{ amperes,}$$

or

$$\cdot 0283 \text{ ampere.}$$

Lost Volts.

Suppose that we have a circuit consisting of a battery of E.M.F. E volts and resistance B ohms, in series with a resistance of R ohms. Then if C amperes flow in the circuit

$$C = \frac{E}{B + R}$$

or

$$E = CB + CR$$

Now the P.D. between the ends of a resistance of R ohms carrying a current of C amperes is, by Ohm's Law, CR volts; so, of the total E.M.F. of the battery, the portion CB volts is used up in driving the current through the cell itself. This portion is often termed *lost volts.*

It is important to take these 'lost volts' into account: for example, when it is desired to light a glow-lamp by means of a battery, if the lamp is a '10-volt' one, i. e. if 10 volts must be maintained at its terminals, a battery of cells giving 10 volts on a voltmeter (when it is furnishing no current) will be insufficient to light the lamp.

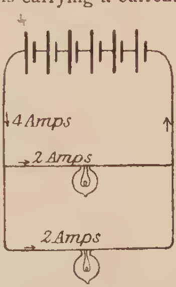


Fig. 72 *c*.

As an example of this, suppose the current which flows through the lamp is 2 amperes when the above P.D. is maintained at its terminals, and that the resistance of the battery is 1 ohm, the lost volts will be 2×1, or 2 volts, so that the total E.M.F. of the battery when furnishing no current ('on open circuit') must be $10 + 2$, or 12 volts. This could be provided by 6 chromic acid cells, the resistance of each of them being $\frac{1}{6}$ ohm. If the battery is to light two lamps as shown in Fig. 72 *c*, each will need 2 amperes,

so that 4 amperes will flow through the cells; and this can be attained by using 6 cells, each larger than the above, so that the resistance of each is only $\frac{1}{12}$ ohm; then the total battery resistance is $\frac{1}{2}$ ohm, and the 'lost volts' $4 \times \frac{1}{2}$, or 2, volts as before; or by using 7 cells, each of very slightly less resistance, $\frac{1}{7}$ of an ohm, providing 4 volts for lost volts.

Error in calibrating a voltmeter by means of a standard cell.

It can now be seen how far the method described in Art. 104 is incorrect.

Suppose that the combined resistance of the galvanometer and resistance is R ohms, and of the cell is B ohms, and that C amperes flow in this circuit: then the P.D. between the terminals of the voltmeter is $C\,R$ volts. This is not exactly equal to E volts, the E.M.F. of the cell, as we have assumed it to be; the error is $C\,B$ volts (the lost volts), or expressed as a fraction, the error is $\frac{C\,B}{C\,R}$ of the reading. If R is very large compared with B, this error is negligible, and the deflection of the instrument (which actually corresponds to $C\,R$ volts, the P.D. between its terminals) may be taken as representing E volts.

Example III. Consider a circuit composed of two cells in series, each of E.M.F. 2 volts, and internal resistance ·01 ohm, and 5 glow-lamps in parallel, each of resistance 4 ohms; required the current in each lamp.

If the equivalent resistance of the group of lamps be called B ohms, then

$$\frac{1}{B} = \frac{1}{4} + \frac{1}{4} + \frac{1}{4} + \frac{1}{4} + \frac{1}{4} = \frac{5}{4}.$$

So $B = \frac{4}{5} = \cdot 8$ ohm.

So the total resistance is $2 \times \cdot 01 + \cdot 8$, or ·82 ohm, and the E.M.F. is 4 volts, so the current through the battery is $\frac{4}{\cdot 82}$, or 4·9 amps., and each lamp carries a current of $\frac{4 \cdot 9}{5}$, or ·98 amp.

120*. Grouping of cells in a battery. If a battery consists of several cells, of the same E.M.F., in parallel, the E.M.F. of the battery is that of a single cell, but their equivalent resistance must be determined as for wires in parallel.

For example, suppose that we have three cells coupled in parallel, each of E.M.F. 1·45 volts, and of resistance ·5, ·8, and ·4 ohm; what current will they send through resistances of (*a*) ·1 ohm, (*b*) 2 ohms?

The equivalent resistance (B ohms) of the battery is given by

$$\frac{1}{B} = \frac{1}{\cdot 5} + \frac{1}{\cdot 8} + \frac{1}{\cdot 4} = 5\cdot 75$$

so
$$B = \frac{1}{5\cdot 75} \text{ or } \cdot 174 \text{ ohm.}$$

So the current which this battery will send through the circuit (a) is

$$\frac{1\cdot 45}{\cdot 1 + \cdot 174} \text{ or } \frac{1\cdot 45}{\cdot 274} \text{ or } 5\cdot 3 \text{ amps.};$$

and through (b) is $\dfrac{1\cdot 45}{2 + \cdot 174}$ or $\dfrac{1\cdot 45}{2\cdot 174}$ or $\cdot 67$ amp.

Next, consider what will happen if the battery consists of these cells in series. The current in (a) will be

$$\frac{3 \times 1\cdot 45}{\cdot 5 + \cdot 8 + \cdot 4 + \cdot 1} \text{ or } \frac{4\cdot 35}{1\cdot 8} \text{ or } 2\cdot 42 \text{ amps.};$$

and through (b) will be

$$\frac{3 \times 1\cdot 45}{\cdot 5 + \cdot 8 + \cdot 4 + 2} \text{ or } \frac{4\cdot 35}{3\cdot 17} \text{ or } 1\cdot 37 \text{ amps.}$$

So if a large current is desired, it is best to group the cells in parallel for the circuit (a), and in series for (b).

Although it now possesses very little practical importance, we may here consider the possible methods of grouping cells.

If we have n cells, each of E.M.F. E volts and resistance R ohms, arranged in series, the E.M.F. of the battery will be nE volts and its resistance nR ohms.

If now we have m such strings of cells, and couple the end poles of each string so as to put them in parallel, the E.M.F. of the battery will be the same as that of each string, i.e. nE, but the resistance will only be $\dfrac{1}{m}$th of its former value, i.e. $\dfrac{nR}{m}$. Hence, if the external resistance is X ohms, the current will be

$$\frac{nE}{X + \dfrac{nR}{m}} \text{ amperes.}$$

If with a given number, $n \times m$ suppose, of cells of given E and R we desire to produce the maximum current through a given external resistance X, it can be shown mathematically that this will be attained when $\dfrac{nR}{m}$ is as nearly as may be equal to X, that is, when the internal and external resistances are equal. This principle was of importance before the invention of the dynamo and accumulator.

T. 121. EXPERIMENT 65. **Reduction factor of a tangent galvanometer by Ohm's law.** If we know the E.M.F. and resistance in a circuit, we can calculate the current flowing in it, and if the circuit contains a tangent galvanometer, by observing the deflection produced by this known current we can find the reduction factor (K).

Take a battery whose resistance is negligibly small, or known from Experiment 63; measure its E.M.F. by a voltmeter. Take the tangent galvanometer whose reduction factor is to be found, and whose resistance is supposed to be known, or to have been measured simultaneously with that of the battery as in Experiment 63. Connect these in series with a suitable known resistance, the galvanometer being connected through a commutator, and the resistance being such as to give a deflection (δ) of the galvanometer between 25° and 70°.

Take the tangent of this angle. Then if E volts be the E.M.F. of the battery, B ohms its resistance, G ohms that of the galvanometer, R ohms that of the interposed resistance, by Ohm's law the current will be

$$\frac{E}{B+G+R} \text{ amperes.}$$

Again, the current is $K \tan \delta$ amperes (see p. 85).

$$\therefore \quad K \tan \delta = \frac{E}{B+G+R},$$

from which K can be found.

The accuracy of this method depends on that of the voltmeter. unless the sensitiveness of the galvanometer is so small that R must be small also, thus allowing the inevitable uncertainty as to the value of $B+G$ to produce a serious error in the value of $B+G+R$. Hence it is not an extremely accurate method, but in many cases better than any of those hitherto given for determining K. As has been mentioned earlier, the reduction factor of a tangent galvanometer is a quantity liable to variation with the position of the galvanometer in the laboratory, a variation from which an ammeter is exempt.

122. It must be clearly understood that a similar relation holds between current, E.M.F., and resistance, whatever may be the units in which they are measured; the more general statement of Ohm's law for a complete circuit would be, *The current in a circuit varies directly as the E.M.F. and inversely as the resistance.* If C represent the current, E the E.M.F., and R the resistance, then $C = K \times \frac{E}{R}$, where K is some number which is constant, however

the current, &c., alter, but which depends on the magnitude of the units in which C, E, and R are stated. The practical units used above were chosen, so that for them this number is 1, and in any other system after choosing any two of the three units independently, the third may be chosen so as to make $K = 1$.

CHAPTER X

Measurement of E.M.F. and Resistance

123. The Potentiometer. The results of Experiment 61 lead us to a method, invented by Poggendorff, for accurately comparing the E.M.F. of cells; its chief merit being that it is a 'null method,' that is, one in which a condition of things is sought for in which *no* current is produced. The attainment of this state of balance can be determined with a higher degree of accuracy than is possible in the measurement of a current (see p. 94).

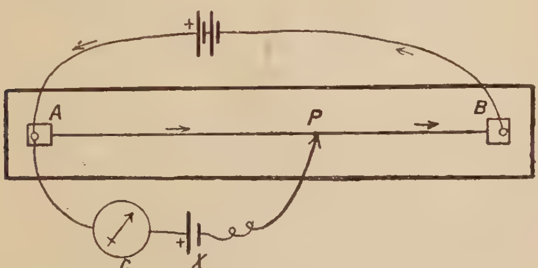


Fig. 73.

In the apparatus as arranged in Fig. 66, a small current flows through the voltmeter from A to P. This could only be stopped by interposing either an infinitely large resistance in this wire, *or* a cell which tried to force a current in the direction from P to A, with exactly the same electromotive force as that which is driving it from A to P; i. e. the P.D. measured in Experiment 61 as being maintained on the wire between A and P.

If, then, we have apparatus arranged as in Fig. 73, where $A\,B$ is a 'potentiometer,' G a very sensitive galvanometer, and X a cell * (whose E.M.F. must be smaller than that of the battery which maintains

* Care must of course be taken to connect the cell X so that it opposes the current in $A\,G\,P$, i.e. the poles of the same kind must both be connected to A.

a current in *A B*), a point can be found for *P* along *A B* so that no current flows along the branch wire *A G P* (as shown by the absence of deflection of *G*).

When this is the case the E.M.F. of the cell will be equal to the P.D. between *A* and *P* on the wire.

If another cell (*Y*) be substituted for *X*, the point *Q* corresponding to *P* can be found similarly. Then provided the current along *A B* is unchanged, the E.M.F. of these cells *X* and *Y* will, by Experiment 61, be in the same proportion to one another as the resistances *A P*, *A Q*, that is, as the lengths *A P*, *A Q*.

EXPERIMENT 67. **To measure the E.M.F. of a cell.** For convenience and speed of substitution of one cell for another, a two-way

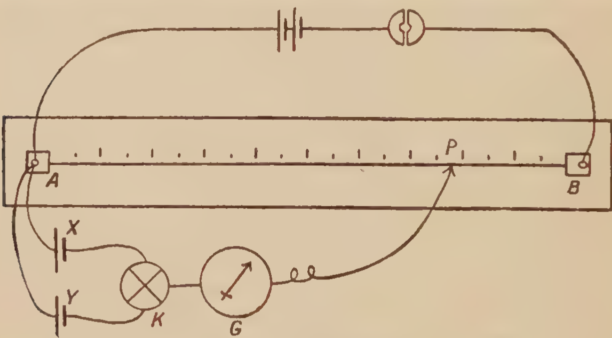


Fig. 74. Potentiometer.

key (*K*)* should be used, and the apparatus should be connected as in Fig. 74.

One of the cells must be of known E.M.F.; a Latimer Clark cell is generally used, and in this case it is advisable to interpose between *G* and *P* a resistance of a few thousand ohms in order to check the passage of any but a very small current. When the approximate position of *P* has been found (in which the E.M.F. of the cell balances the P.D. due to the current in *A P*), the resistance should be cut out, in order to use the full sensitiveness of the galvanometer in discovering the exact position.

The first operation should be to make contact with *P* near *A*, and then near *B*, when one of the cells *X* or *Y* is in circuit; *G* should show deflections in opposite directions. If this is not the case, the

* Or a plug commutator (Fig. 55, p. 84) using only one plug.

required point giving no deflection cannot lie between these two points; either the connections have been wrongly made, or the E.M.F. between A and B produced by the battery is not sufficient.

If this test is satisfactory, switch in the Clark cell and move P along $A\,B$ until no deflection of G occurs on making contact. Note the length $A\,P$; call it l_1 cm.; then we know by Ohm's law that the P.D. in volts per cm. of the wire is $\frac{1{\cdot}434}{l_1}$.

Switch in the unknown cell instead of the Clark cell, and find the corresponding point Q. Note the length $A\,Q$ (l_2 cm., say). Then the P.D. between A and $Q = l_2 \times \frac{1{\cdot}434}{l_1}$ volts.

This is the E.M.F. of the unknown cell.

123 a. Having in this manner accurately determined the E.M.F. of a cell, such as a Daniell, it is worth while to check with it the accuracy of graduation of the voltmeter you have been using.

But the following is a better way of checking the accuracy of a voltmeter.

EXPERIMENT 67 *a*. **Accurate calibration of voltmeter.** Set up a potentiometer $A\,B$, with two accumulators to maintain current in the wire $A\,B$ (Fig. 74 *a*). Connect one terminal of the voltmeter to be tested to A, the other to some point S of $A\,B$ (if the P.D. between A and B is within the range of the voltmeter, S may conveniently be at B). Observe the reading of the voltmeter. Keeping the voltmeter in parallel with $A\,S$, connect a Clark standard cell Y, in series with a galvanometer G, to A and to a point Q on $A\,B$; find a position of Q for which G shows no deflection. Then as before the P.D. between A and S is $\frac{A\,S}{A\,Q} \times 1{\cdot}434$ volts, which should be the reading of the voltmeter.

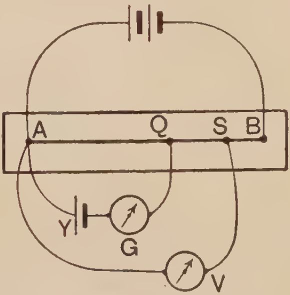


Fig. 74 *a*.

Note that the voltmeter is taking current throughout the experiment, so the current in $S\,B$ is greater than in $A\,S$; but since Q is in such a position that no current flows along $A\;Y\,Q$ the current and therefore the P.D. from point to point

of the wire $A\,S$ is uniform, provided that $A\,S$ is longer than $A\,Q$. The accuracy of the result is entirely independent of the resistance of the voltmeter. It will be evident that a Potentiometer is in itself the most accurate form of voltmeter.

123b*. If we wish to calibrate a voltmeter for readings below 1·4 volts, we can use the following arrangement; it is less simple than that in Art. 123 *a*, but it is also more convenient for verifying a number of scale divisions of the voltmeter, whether above or below 1·4 volts.

EXPERIMENT 67 *b*. Set up a potentiometer $A\,B$ as in Fig. 74 *b*, Y being a Clark cell, $R\,Q$ a fixed resistance through which current can be passed from the battery M through the variable resistance $S\,T$. V is the voltmeter to be tested, A an ammeter not needed until the next experiment; the other apparatus is as in Experiment 67.

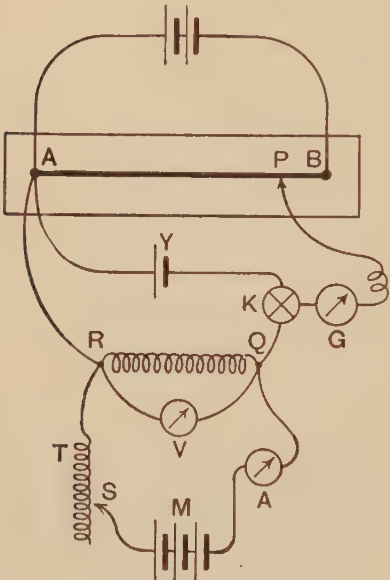


Fig. 74 *b*.

Setting the key K to connect Y and G, determine as usual the P.D. per cm. of $A\,B$. Now adjust the resistance $S\,T$ until the P.D. between R and Q, as shown by V, is on the scale division of V which it is required to check; set K to connect G with Q. $R\,Q$ now replaces the unknown cell in Fig. 74, Art. 123, and the P.D. between R and Q can be determined as described in that Article (by adjusting P until G shows no current, and calculating the P.D. between A and P). Hence the error of V at that point of the scale is determined.

By altering $S\,T$, other divisions of V can be checked without redetermining the P.D. per cm. along $A\,B$, as was necessary in Experiment 67 *a*.

We can use the apparatus of Fig. 74 *b* to calibrate an ammeter

by a standard cell and standard resistance, instead of directly by copper deposition, as follows.

EXPERIMENT 67 *c*. **To calibrate an ammeter.** The voltmeter shown in Fig. 74 *b* is not required; *A* represents the ammeter to be calibrated. The value of the resistance *R Q* must be accurately determined by a wire bridge and standard coil, and it should be constructed of wire (such as platinoid or manganin) whose temperature coefficient (p. 129) is negligibly small, so that its resistance is unaltered by the current flowing through it. Call this resistance *r* ohms. Determine, as in Experiment 67 *b*, the P.D. between *R* and *Q* when a current giving the required deflection of *A* is passing round the circuit *M S T R Q A*; call this *v* volts.

Then by Ohm's Law, the true current through *R Q* is $\frac{v}{r}$ amperes. This is the true current through *A*, since none passes through *G*; hence the error of reading of *A* is determined for that graduation. By altering *S T* any other graduation of *A* can be checked.

124. Wheatstone's bridge. Suppose a battery *C* (Fig. 75) is connected by copper wires to two points *A* and *B*, which are connected by two wires *A P B* and *A Q B*. The current furnished by *C* will divide at *A*, and part (C_1 amps., say) will flow viâ *P*, and part (C_2 amps.) viâ *Q*; these will rejoin at *B* and flow on to the battery. These two currents will be maintained by a P.D. along both *A P B* and *A Q B*, *which must be the same in each case*, since *A* and *B* are common to both circuits.

Now consider any point *P* in *A P B*. Call the resistance of *A P*, R_1 ohms, and of *P B*, r_1 ohms; call the P.D. between *A* and *P*, V_1 volts and between *P* and *B*, v_1 volts.

Then by Ohm's law $$C_1 = \frac{V_1}{R_1} \text{ and } C_1 = \frac{v_1}{r_1},$$

so $$\frac{V_1}{R_1} = \frac{v_1}{r_1},$$

and $$\frac{V_1}{v_1} = \frac{R_1}{r_1} \quad \text{. . . . . (i)}$$

Next consider any point *Q* in the wire *A Q B*; calling the corresponding quantities V_2, v_2, &c., we have by similar reasoning

$$\frac{V_2}{v_2} = \frac{R_2}{r_2} \quad \text{. . . . . (ii)}$$

There must be some point Q in $A\,Q\,B$ such that the P.D. between A and Q is V_1 volts. Suppose now that Q is this point, so that

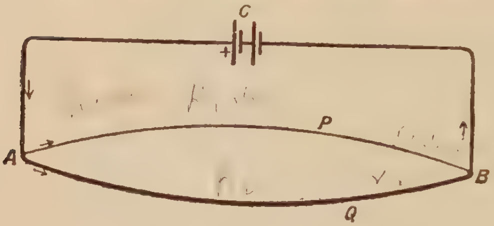


Fig. 75.

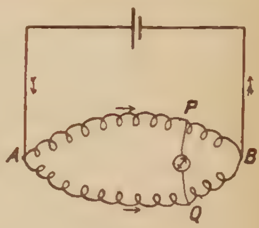


Fig. 76.

$V_2 = V_1$; since the total P.D. along $A\,P\,B$ is the same as that along $A\,Q\,B$ (i.e. $V_1 + v_1 = V_2 + v_2$), the P.D. between Q and B must be v_1 volts (i.e. $v_2 = v_1$).*

So there is no P.D. between P and Q, and if P and Q are connected together by a wire no current will flow along it. If, however, we connect P by a wire to any other point of $A\,Q\,B$, a current will flow one way or the other; so that if we include a galvanometer in the wire $P\,Q$ (as in Fig. 76) the absence of deflection will show when we have found the correct position of Q. In that case the left-hand members of equations (i) and (ii) are equal; hence

$$\frac{R_1}{r_1} = \frac{R_2}{r_2}.$$

So, finally, if P and Q are so chosen that no current flows along $P\,Q$ when joined by a wire, the following relation exists between the resistances:

$$\frac{\text{resist. between } A \text{ and } P}{\text{resist. between } P \text{ and } B} = \frac{\text{resist. between } A \text{ and } Q}{\text{resist. between } Q \text{ and } B}.$$

125. The **Wheatstone's bridge method** of measuring resistances is based on this principle; the two most common forms of instrument

* These points P and Q are related to one another like the negative poles of two cells of exactly equal E.M.F. whose positive poles are coupled together at A (or like the positive poles of two such cells whose negative poles are connected at B); if the free poles are connected by a wire no current will flow along it since there is no balance of P.D. tending to drive electricity either way along the wire.

Reverting to the analogy of water pressure (mentioned on p. 98), it is as though a rapid stream divided and joined again, forming an island. It must be possible to dig a channel across this island from any point on one side of it to some point on the other, so that no stream flows through that channel; these points will of course be on the same *level*.

for applying it are called respectively the B.A. (British Association) Wire Bridge, and the Post Office Box.

EXPERIMENT 68. **Measurement of resistance by the wire bridge.** The ordinary form for the B.A. bridge consists of a platinoid wire one metre (or sometimes half a metre) long stretched alongside of a scale on a board. Connections with binding screws (*C*, *D*, *E*, *F*, *G*) are made as in the diagram (Fig. 77) by thick copper straps, whose resistance is practically nothing.

A contact-maker, carrying a binding screw, is arranged to slide along the board so as to make contact at any point of *A B*, and to show on the scale the exact distances from *A* or *B* at which contact is made; since the wire is uniform, the resistances of the two portions, into which the wire is divided, are in the same proportion as their lengths. This contact-maker generally carries a spring, so that no contact is made until the spring is depressed.

The battery used to produce a current along *A B* and through the other branch consists of one or two Leclanché cells. The galvanometer should be as sensitive as possible; as this is a null method it

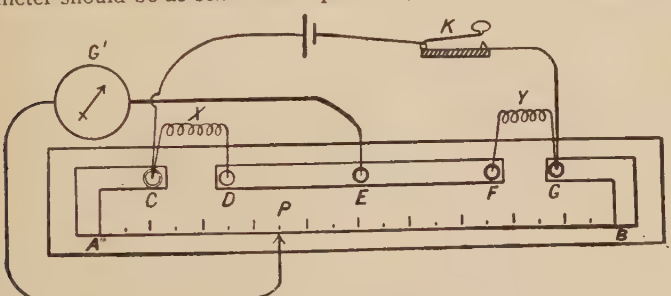


Fig. 77. Wire Bridge.

need not be a measuring instrument, so that an astatic galvanometer will serve admirably, or a moving coil or mirror galvanometer. A low-resistance galvanometer will be most efficient.

Connections must be made as in Fig. 77.

Here *K* is a tapping-key to join up the battery just before contact is made at *P*; *X* and *Y* are resistances, *X* being that to be measured, and *Y* a standard coil. The binding screws at *C* and *G* are double, to accommodate the two wires connected at these points.

Until the approximate position of *P* has been found, the galvanometer *G* should be 'shunted' (see p. 105), or a resistance should be

included in the galvanometer circuit; either must be cut out before the final determination of the position of P is made.

When a balance has been obtained, carefully read the distance of P from A and B; we then have

$$\frac{\text{resist. of } X}{\text{resist. of } Y} = \frac{\text{resist. of } AP}{\text{resist. of } PB} = \frac{\text{length of } AP}{\text{length of } PB}.$$

Hence calculate the resistance of X.

The greatest accuracy will be got when the position of P is not far from the centre of AB; if it is near either end, a small error will have a serious effect (cf. the tangent galvanometer), so that although theoretically such an arrangement will serve to measure a resistance of any magnitude, in practice it is necessary to choose as the standard coil Y, one whose resistance is not very different from that of X, say half to twice as great.

Determine in this manner the resistance of some unmarked coils of wire; that of half a metre of thin platinoid wire, and of the resistance coil made in Experiment 47. If the error of the latter is small, it should be marked on it; if large, the correct length of the wire should be calculated, and the coil remade.

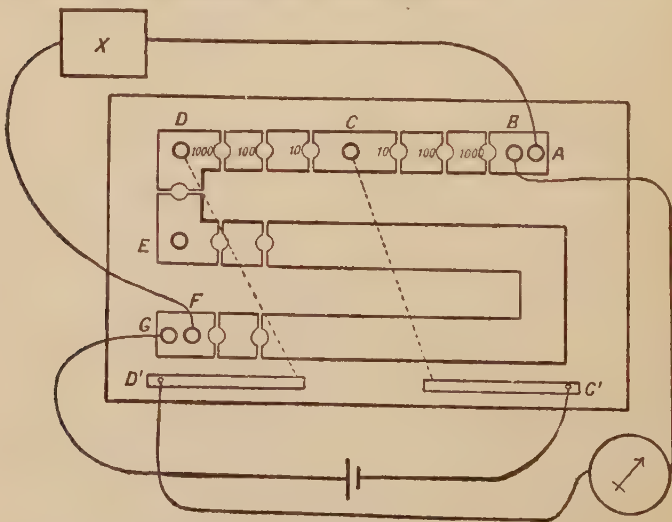


Fig. 78. Post Office Box.

126. Post Office box. For the purposes of the workmen of the G. P. O. a portable instrument for the measurement of resistance is

required, and this is furnished by the Post Office box, of which a bird's-eye view is given in Fig. 78.

It consists of an ordinary resistance-box, with some additional coils and binding screws. In many cases two tapping-keys are provided on the top of the box, so that wires connected to binding screws at C' and D' may be put in contact with C and D respectively when these keys are depressed. This is effected by means of wires underneath the top as shown by dotted lines.

A plug is often provided between D and E, there being no coil to bridge this gap inside the box. In use as a Post Office box the plug must be in its place; but when it is pulled out, the box furnishes two separate resistance-boxes.

EXPERIMENT 69. **Measurement of resistance by Post Office box.** The method of using the box on the Wheatstone's bridge principle will be seen from the connections in Fig. 79, where the binding screws have the same letters as in Fig. 78.

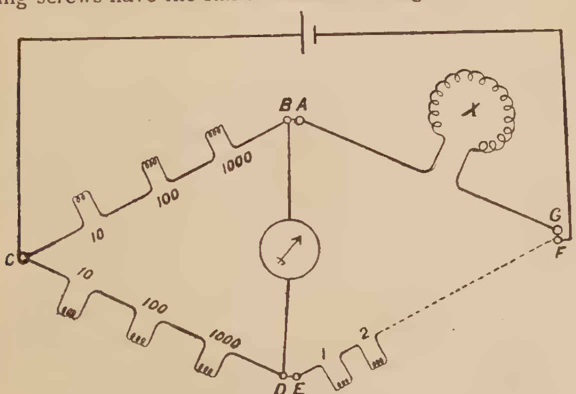


Fig. 79.

Instead of moving the end of the wire from the galvanometer along a uniform wire as in the B.A. bridge until a 'balance' is obtained (i.e. until no current flows through the galvanometer), the galvanometer wire is fixed, and three of the resistances (CB, X, and CD) are kept constant; the balance is obtained by changing the resistance in EF to the required amount. When this is the case,

$$\frac{\text{resist. in } CB}{X} = \frac{\text{resist. in } CD}{\text{resist. in } EF},$$

or
$$X = \frac{\text{resist. in } CB}{\text{resist. in } CD} \times \text{resistance in } EF.$$

If the resistance in CD is made the same as in CB the value of the unknown resistance is simply that in EF; it can then be read off directly from the plugs which are out.

If, however, X is small compared to the available resistance in EF, we insert 100 ohms into CD and 10 ohms into CB; then X is one-tenth the resistance in EF, since

$$X = \frac{10}{100} \times \text{resist. in } EF.$$

Thus, if the smallest coil provided in EF is 1 ohm, we get the value of X correct to one place of decimals.

By substituting the 1000-ohm coil in CD, we can measure X correct to two places of decimals.

If, however, X is very large, we can insert the 100- or 1000-ohm coil in CB, and the 10-ohm coil in CD, and then the value of X will be 10 or 100 times the resistance in EF when a balance is obtained.

For ordinary resistances it is best to begin with a 10-ohm coil in both CB and CD, and having got X correct to an ohm, to substitute 100 for 10 ohms in CD, and find the resistance in EF then required to produce a balance; and so on.

The connections with the actual box will be as shown in Fig. 78.

The student should not attempt to remember these connections, but should recover them by drawing diagrams of the typical Wheatstone's bridge, as Fig. 76, and the theoretical Post Office box, as Fig 79, and so obtain the connections with the actual box before him. If no tapping-keys are provided on the box they must be inserted separately; and it is convenient to shunt the galvanometer (which must be very sensitive) until a balance has nearly been obtained.

The method of conducting an experiment is as follows. Having coupled up as above, take out plugs giving 10 ohms in both CB and CD; take out no plug from GE. Depress the keys, *first* C' then D' (still holding down C'). The galvanometer should be deflected. Take out the highest resistance, or the infinity plug, from GE, and again depress the keys. The galvanometer should now be deflected in the opposite direction; if no deflection occurs, or one in the same direction as before, some connection must be wrongly made.

Now work downwards through the resistances in GE, exactly as if they were weights, until no deflection occurs on tapping the keys; remove the shunt from the galvanometer when necessary.

Then the resistance in GE is, correct to 1 ohm, that of the 'unknown' X.

Next put into GE a resistance ten times the one thus found, and

substitute 100 ohms for 10 ohms in CD. Again obtain a balance; the value of X correct to ·1 ohm will now be found by dividing the resistance in GE by 10.

Repeat with 1000 ohms in CD.

127. In ordinary laboratory practice, the Post Office box is better adapted to the measurement of large, the wire bridge to that of small, resistances.

128. Specific resistance. It was shown in Experiment 44 that the resistance of wires depends, *ceteris paribus*, on the material of which they are made. The resistance in ohms offered by a length of 1 cm. of a 'wire,' whose cross-section has an area of 1 sq. cm., is called the **specific resistance** of the material of which the wire is made. This may also be expressed shortly, but less accurately, as follows: the specific resistance of a material is the resistance between opposite faces of a unit cube of that material.

It will be noted that in this connection the word 'specific' has not the same meaning as in specific heat, specific gravity, &c., since no direct comparison with a standard substance is implied; but since the ohm is defined as the resistance of a 'wire' of mercury of a certain size, there is an indirect comparison.

Specific Resistance of Substances.

In *millionths* of an ohm; 1 cm. cube at 0° C.

Copper (annealed)	1·57.
Silver	1·49.
Platinum	9·0.
Iron (com$^{l\cdot}$)	15·0.
Mercury	94.
Carbon (arc light)	4000 about.
German silver	21.
Platinoid	32·5.
Manganin	40·8.

Liquids at 13° C.

Dilute sulphuric acid 30%	$1·37 \times 10^6$.
Dilute zinc sulphate	3×10^7.
Dilute nitric acid 30%	$1·29 \times 10^6$.

129. The following laws show how the resistance of a conductor depends on its length, cross-sectional area and material.

(1) *The resistance of a conducting wire is proportional to its length.* This was assumed, or included in the definition of resistance, on p. 71.

(2) *The resistance of a wire is inversely proportional to the area of its cross-section.*

This may be considered self-evident, since two wires, side by side, must offer half the resistance of one similar wire, and when fused into one would form one of twice the area of cross-section of either; and an extension of the same reasoning would prove it for any proportion between the areas of cross-section. This is unsound reasoning, however, unless we have proved that the current in a wire is uniformly distributed throughout it, and is not, for example, confined to the outer skin of the wire. We know that the latter is the case for rapidly alternating currents, so that this law is not true for them; for continuous currents, however, it is true, and may readily be shown to be true by measuring the resistance of wires of the same material and length, but different thickness, by means of the Wheatstone's bridge.

In the case of wires of circular section, the law can be stated thus: '*the resistance of a wire is inversely proportional to the square of its diameter,*' since the area of a circle is proportional to the square on its radius, and the diameter is twice the radius.

(3) *The resistance of a wire is proportional to the specific resistance of the material of which it is made.*

These three laws can be united into one statement as follows:—if l cm. is the length of the wire, A sq. cm. the area of its cross-section, ρ the specific resistance of the material, then its resistance is

$$\frac{\rho l}{A} \text{ ohms.}$$

EXPERIMENT 70. **To prove that the resistance of a wire varies inversely as the area of its cross-section.** Take two pieces of platinoid wire of the same material but different thickness, say No. 24 and 36. The length of the thinner wire should be about one quarter that of the other, in order that the resistances may be about the same.

Arrange them in the gaps of a B.A. bridge connected up as in Experiment 68, and find the ratio between their resistances.

Measure the diameter of each wire. The best method of doing this is to use a screw gauge, taking readings at several points where

the wire cannot have been subjected to any flattening, and taking care not to screw up the gauge so as to flatten the wire; the 'zero error' of the gauge must also be determined and allowed for. A second but rougher method is to use a standard wire-gauge, which consists of a sheet of metal with slots cut in its edge, of such a breadth as to just permit the passage of wire of the corresponding gauge. The diameter of the wire can then be found from the table on p. 292.

Suppose that the respective lengths of the wires are l_1, l_2 cm.; the diameters d_1, d_2 cm., and therefore since they are circles, the areas of the cross-sections $\pi\left(\frac{d_1}{2}\right)^2, \pi\left(\frac{d_2}{2}\right)^2$ sq. cm.; and the ratio of the resistances of the first and second, as determined by experiment, λ.

The first wire has a resistance λ times as great as the other, and is $\frac{l_1}{l_2}$ times as long. If it were reduced to the same length, its resistance would only be $\frac{\lambda}{\frac{l_1}{l_2}}$ times as great as the other, or

$$\frac{\lambda l_2}{l_1}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (A)$$

But the areas of cross-section of the wires are respectively $\pi\left(\frac{d_1}{2}\right)^2, \pi\left(\frac{d_2}{2}\right)^2$, since they are circles.

$$\therefore \text{ their ratio is } \frac{d_1^2}{d_2^2}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (B)$$

Compare the values you find for (A) and (B).

The question could, of course, have been settled by actually measuring in ohms the resistance of each wire, but this method is shorter.

This experiment shows that the current distributes itself evenly throughout the wire in which it flows.

EXPERIMENT 71. **To measure the specific resistance of a metal.** Take a thin wire of the given material, say platinoid. Measure as in Experiments 68 or 69 the resistance (R ohms) of a known length (l cm.) of this wire. Determine the diameter (d cm.) of the wire, either directly by a screw gauge, or indirectly by a standard wire-gauge and the table on p. 292.

Then if ρ be the specific resistance, we have, as on p. 126,

$$R = \rho\frac{l}{A}, \text{ and } A = \frac{\pi d^2}{4};$$

$$\therefore \quad \rho = \frac{\pi R d^2}{4l}.$$

If the problem is to *compare* the specific resistances of two metals, we may proceed as follows. Take a B.A. wire bridge, and in one of the gaps insert a length of thin wire made of the one metal, and in the other gap an *equal* length of wire of the other metal. For an accurate result it is best to have the material of higher specific resistance made into the thicker wire.

Find the ratio (λ) between the resistances of the wires, and the diameter of each (d_1, d_2, suppose).

Then if the specific resistances are denoted by ρ_1, ρ_2, and the length of each is l cm., if the resistances of the wires are R_1, R_2,

$$\rho_1 = \frac{\pi R_1 d_1^2}{4l}, \quad \rho_2 = \frac{\pi R_2 d_2^2}{4l}.$$

$$\therefore \quad \frac{\rho_1}{\rho_2} = \frac{R_1 d_1^2}{R_2 d_2^2} = \lambda \frac{d_1^2}{d_2^2}.$$

130. The values found in Experiment 71 for the specific resistance of the metals tested will not necessarily be incorrect if they do not agree with the table on p. 125, because the admixture of a minute proportion of another metal considerably increases the resistance. Thus if the highest conductivity is desired, purity is essential, and in the case of platinoid, &c., if a certain specific resistance is desired, absolute uniformity in the proportions of the constituents must be secured. As an example of this, if the conductivity of pure copper be taken as 100, the introduction of 1·6 per cent. of silver (which is a better conductor than copper) reduces it to 65.

Again, as will be seen in the next experiment, the specific resistance of a metal depends on its temperature, and this must be taken into account before comparison can be made with the above table.

EXPERIMENT 72. **Effect of temperature on the resistance of a conductor.** Get a coil of silk-covered copper wire, say 2 metres, No. 36 (or an *open* coil of uncovered iron wire, about 1 metre of No. 28, see Appendix, p. 292), having a resistance of about 1 ohm. Solder this to a pair of leads of thick copper wire about 20 cm. long; a piece of double wire made for the line wires for electric bells is convenient.

Measure with a Wheatstone's bridge the resistance of the coil and leads, when the coil is immersed in a beaker containing a mixture of ice and water, and again in boiling water; then, by joining together the ends of the leads near the points of contact with the coil, measure the resistance of the leads (unless this resistance was measured before the coil was soldered on).and so deduce the resistances

of the coil when at 0° C., and at the temperature of boiling water. Let this latter temperature be $\theta°$, and let the two resistances be R_0, R_θ respectively.

Then the average increase of resistance of copper (or iron), *per ohm* measured at 0°, per degree centigrade is

$$\frac{R_\theta - R_0}{R_0 \theta}.$$

131. The number found in Experiment 72 is called the 'temperature coefficient' of the metal; it is found to be nearly constant whatever be the upper temperature chosen instead of 100° C., i. e. the resistance of copper is found to increase nearly uniformly with the temperature, so that if a be the value of the temperature coefficient, and R_θ be the resistance at temperature $\theta°$ C.

$$\begin{aligned} R_\theta &= R_0 + a R_0 \theta \\ &= R_0 (1 + a\theta). \end{aligned}$$

The value of a for all pure metals is found to be very nearly the same, about ·004. For alloys it is very much less, hence alloys are used for resistance-coils, since their resistance is much higher and less variable with temperature than if made of any pure metal. For example, a for German silver (copper 60 parts, zinc 26, nickel 14) is about ·0004; for platinoid (German silver with about 1 per cent. of tungsten) about ·0002; manganin (copper 84 parts, manganese 12, nickel 4) has a zero temperature coefficient, and a resistance as high as platinoid.

The behaviour of carbon is anomalous, as it has a *negative* value of a (about − ·0005), i. e. its resistance decreases with increase of temperature. For example, the filament of a glow-lamp may have a resistance when cold of 900 ohms, but only 600 ohms when heated white-hot by the current. In the Nernst lamp the rod of infusible earth is a non-conductor when cold, but conducts fairly well when white-hot. This is characteristic of 'electrolytic conduction' (p. 165), which is probably the process in a Nernst lamp; but there is nothing else to suggest electrolytic conduction in carbon.

132. Callendar's pyrometer. The measurement of resistance is a process susceptible of the highest degree of accuracy, so that the changing resistance of a platinum wire will furnish a means of determining the changing temperature to which it may be exposed.

This method of temperature measurement has been brought to perfection by Professor Callendar; the utility of his pyrometer or electric thermometer ranges between a blast furnace and liquid air, and by it a temperature can be read by an unskilled workman, or the blast furnace may be made to record its temperature in an office at any required distance away.

CHAPTER XI

Electro-magnetics

133. If a fairly large current, say 5 or 10 ampères, be made to flow along a vertical straight wire, which passes through a hole in a horizontal piece of cardboard on which some iron filings have been sprinkled, these filings will arrange themselves in circular chains, with the hole as centre.

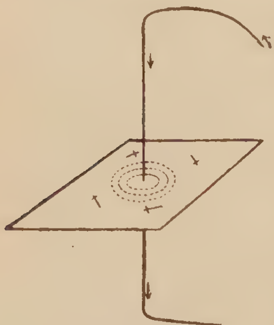


Fig. 80.

This shows (p. 16) that the current in the wire produces round it a field of magnetic force consisting of circular lines of force.

If small compasses be laid on the card the needle will set along these lines, and will point in a sense which may be determined by the 'corkscrew rule' given on p. 50. These compasses will show that the field of force extends far beyond the area in which it is strong enough to affect iron filings.

If now the wire carrying the current is bent round into a nearly complete circle, as in a tangent galvanometer, and is set in a vertical plane, the field of force will be modified into the form shown in Fig. 81, which represents a horizontal section, *A* and *B* being the points where the circular wire cuts the card.

If the current flows down at *B* and up at *A*, the lines of force will have the directions as marked by the arrows, i. e. these will be the directions in which a N. pole will be urged by the current.

If the wire is coiled into a spiral instead of a single turn, the field

of force will become as in Fig. 82, where A, B, C, D, . . . P, Q are the successive points where the wire cuts the card (the current flowing up at A, C, E, &c.). Such a coil, in which successive turns are usually in contact, is called a **solenoid** (σωλήν, a pipe); it can readily be made by closely coiling insulated wire (such as No. 20 cotton covered copper) round a glass tube or circular ruler.

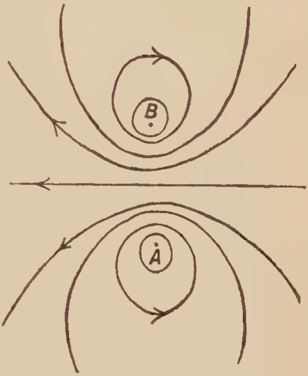


Fig. 81.

It will be seen that the lines of force outside the solenoid are similar to those outside a bar-magnet, so that while the current flows the solenoid is equivalent to a bar-magnet, having its N. pole where the lines emerge from the solenoid, its S. pole where they enter it. The lines of force are most closely crowded together inside the solenoid, and if a bar of soft iron is put there it will be magnetized by induction, and the solenoid with its iron core will act as a much stronger magnet than the solenoid alone.

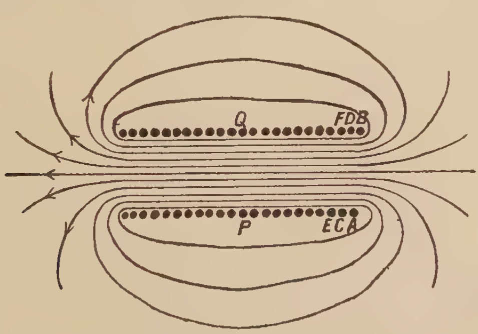


Fig. 82.

Such a combination is called an **Electro-magnet**. If a large current traverses the coil, the iron will be strongly magnetized, and its effect at external points will be much greater than that of a piece of steel of the same size, magnetized as highly as possible as a 'permanent magnet.'

134. Electro-magnets are made in very various shapes, but most commonly in that of a 'horseshoe.' This is made of two cylinders of iron lying parallel to one another, and connected by a thick yoke of iron, each of the cylinders being surrounded with a coil. These coils must be wound in such a manner as to induce unlike poles at the free ends of the cylinders; an examination of Fig. 82 will show how the polarity of the solenoid is connected with the flow of the current. The simplest way to remember this is as follows: Look at the end of the coil; if the current flows clockwise the near end will be S., if counter-clockwise the near end will be N. (Fig. 83).

Fig. 83.

The manner of winding such an electro-magnet is represented diagrammatically in Fig. 84, where *A* and *B* are the two iron cylinders, *C* the iron yoke.

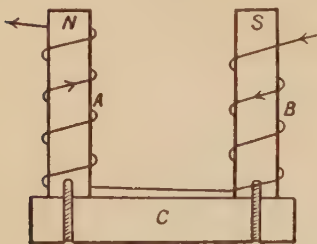


Fig. 84. Electro-magnet.

135. A solenoid of fairly large diameter will be found of great use in a laboratory for magnetizing steel bars to act as permanent magnets, since they can be by this means much more powerfully and uniformly magnetized than by the methods described on pp. 4, 12. For magnetizing horseshoe magnets the most convenient plan is to put the poles on those of a horseshoe electro-magnet and knock the steel while the current is flowing.

If the iron core of the solenoid is made of soft iron, it loses nearly the whole of its magnetism (see p. 5) directly the inducing force of the current stops; so that an electro-magnet can be controlled from any place to which the wires, connecting the battery to the magnet, can be taken. This property is of the greatest importance in many of the practical applications of electricity, such as the electric bell, telegraph, and telephone, which we will now consider.

136. Electric bell. This consists of a fixed electro-magnet (*H*, Fig. 85) provided with a movable keeper (*D*), carrying a clapper (*E*). *D* is supported on a spring, which is fastened to a fixed block *G*

in such a manner that *D* normally stands a little distance away from the electro-magnet, but when attracted towards it moves in such a manner that *E* strikes a bell *F*. The spring carrying *D* is continued into a free end *C*, which, when *D* is in its normal position, touches against a fixed screw *B*; this contact is broken when *D* is attracted by *H*. These points of contact should be armed with little pieces of platinum to resist wear by sparking.

The 'line-wire' is connected to a binding screw *A*, from which the current flows to *B*, thence through *C* to *G*, from which it is led by a wire to and around the electro-magnet *H*, and out to the other line-wire by a binding screw *K*. When the current flows thus, *D* is attracted towards *H*, and *E* hits *F*; but the circuit is broken at *C*, and the spring carries *D* back again, thus remaking contact and renewing the attraction of *H* for *D*.

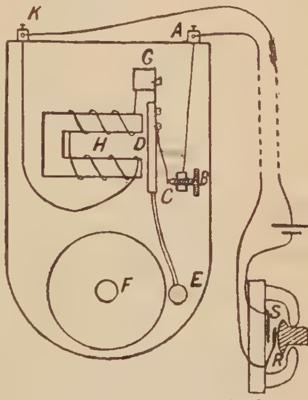


Fig. 85. Electric Bell.

Thus the clapper 'trembles' against the bell as long as current is supplied.

The line-wires are connected up through a battery of one or two Leclanché cells to a 'push' (*P*).

P is the ivory stud by which the spring *R* is pushed into contact with *S*, thus joining the ends of the line-wire and completing the circuit.

137. Single-stroke bell. If, in Fig. 85, *A* is directly connected to *G* by a wire, so that the current does not pass through the contact-breaker (*C*), the bell will give one single stroke each time the circuit is made by pressing the push. In this form the bell can be used for signalling, by the Morse (p. 135) or some other code of signals.

138. Telegraphs. The first devices for electrically conveying signals to a distance employed 'frictional' electricity; the first practical telegraphs worked by voltaic cells were invented by Wheat-

stone about 1837. He used a simple kind of galvanometer at the 'receiving station,' and a commutator and battery at the 'sending station,' and connected them by a pair of insulated wires. By sending currents in one direction or the other the needle of the galvanometer was moved to right or left; each letter of the alphabet was indicated by a certain sequence of such deflections, e.g. one to left and one to right meant *A*, one to right and three to left meant *B*, and so on.

It was discovered * that the earth can be used instead of one of the wires as a path for the current, connection being made at each end to a large conductor sunk in the ground. The other wire must of course be carefully insulated from the earth, usually by being supported on porcelain insulators fixed on poles.

Students often find a difficulty in realizing 'how the current finds its way from the one earth-plate to the other.' It may be easier to think of these two earth-plates as draining off the electricity of opposite signs, as explained in Part III) which would otherwise accumulate in the instruments at each end, thus keeping the two earth-plates at the same potential (zero). The two quantities of electricity then merely flow separately into a practically inexhaustible reservoir.

For sending messages in both directions there must of course be a commutator and galvanometer at each station, but one line-wire will serve.

This form of single-needle telegraph is still in use, especially in railway-signalling, where the most important work is to signal 'train on line,' or 'line clear,' which can be shown by keeping the needle to left or right.

139. The Morse instrument. The form of telegraph most commonly used now is the one devised about 1837 by Morse, an American.

Instead of a galvanometer an electro-magnet (see Fig. 86) is used which, when a current flows through it, draws down an armature usually kept up by a spring, as in the electric bell. This causes a pen to touch a paper ribbon, which is kept moving in front of it by clockwork, making a long or short mark according to the time the current is kept on. If no record of the message is needed, the armature is arranged to make an audible click, which differs in sound at the making and breaking of the circuit, and the receiver of the message listens for the long or short intervals between these clicks.

* By Professor Steinheil, of Munich.

The International Morse Code, by which these 'dots and dashes' represent letters and figures, is as follows:

A . —	J . — — —	S . . .
B — . . .	K — . —	T —
C — . — .	L . — . .	U . . —
D — . .	M — —	V . . . —
E .	N — .	W . — —
F . . — .	O — — —	X — . . —
G — — .	P . — — .	Y — . — —
H	Q — — . —	Z — — . .
I . .	R . — .	
0 — — — — —	4 . . . . —	7 — — . . .
1 . — — — —	5	8 — — — . .
2 . . — — —	6 —	9 — — — — .
3 . . . — —		

For a single-needle telegraph, a dot is replaced by a movement to the left, and a dash by one to the right.

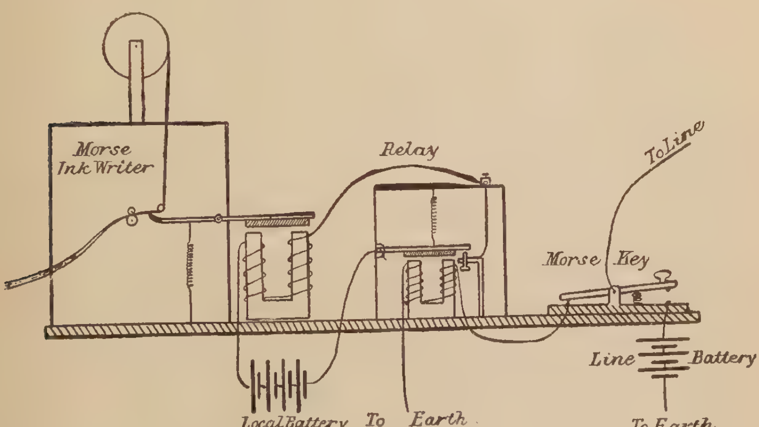


Fig. 86.

This code is well worth learning; it is used in all kinds of signalling.

For 'sending' a Morse key (see Fig. 86) is used. A metal bar can turn about a pivot, when pressed down by a knob; ordinarily a spring keeps

the bar in such a position that it is in contact with a stud, so that the local instrument is connected to the line; but on depressing the knob the bar makes contact with another stud, sending a current through the line to the distant instrument.

140. Since the resistance of the line is large, the current is often too weak to magnetize the electro-magnet with sufficient strength to operate the inking mechanism. For this reason a **Relay** is introduced. It consists of an electro-magnet with a delicately-poised keeper (or, 'armature'), which on being attracted by the magnet makes contact with a stud and so joins up a 'local' circuit containing the Morse instrument and a powerful battery.

The connections at one of the stations are as in Fig. 86.

In the position shown, the Morse key allows a current along the line from the other station to work the relay and therefore the ink-writer; when the key is depressed, a current is sent from the line-battery through the other station, without affecting the instrument at this end.

141. The Telephone transmitter. Sound is transmitted by the air in the form of a series of waves, the pitch of a note depending on the number of these waves which reach a fixed place in a second. When these waves strike against a thin flexible diaphragm supported at its edges, they set it in vibration with the same frequency as their own. In the telephone transmitter there is such a diaphragm, and pressing against it lie granules of carbon. As the diaphragm vibrates backwards and forwards these granules are more or less closely pressed together, so that the resistance to the passage of a current of electricity from one to the other is diminished or increased with every movement of the diaphragm. Arrangements are made whereby a current of electricity flows through the heap of carbon-granules all the time the transmitter is in use, so that when a steady note is sung into such a transmitter, say the middle C of the scale, which produces 256 vibrations of the diaphragm per second, this current will suffer 256 changes of strength per second. This variable current of electricity passes along the line to the receiver, where it is to be re-translated into vibrations of the air, i.e. sound, of the same frequency.

If words are spoken to the diaphragm, the air-vibrations and consequent variations of current are much more complex; but it is the

valuable property of carbon that its changes of electrical resistance faithfully follow the most minute and rapid changes of pressure, hence the minute variations even in the 'shape' of the sound-waves, which distinguish the speech of one person from that of another, are exactly translated into variations of the electric current.

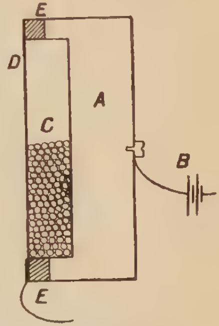


Fig. 87.

Only a very idealized diagram of a telephone transmitter can well be given here, such as Fig. 87. The diaphragm (*D*) is supposed to be a conductor, such as a thin sheet of carbon, *C* being the carbon-granules lying in a box (*A*), also of carbon, separated from *D* by a ring (*E*) of some non-conductor such as cardboard. *B* is the battery, of Leclanché cells, which furnishes the current; it is only in circuit while the instrument is in use.

142. The Telephone receiver. In Fig. 88, *A* is a circular box like a large pill-box, with a round opening in the lid, underneath which is fixed by its edge the thin *iron* diaphragm (*D*). Just below this, with its end not quite touching *D*, is fixed the bar-magnet* *NS*, which has a coil of wire (*C*) round the end inside the box. This coil is connected to the line-wires, so that the variable current from the transmitter traverses the coil. This produces corresponding variations of strength in the magnet, and consequently the iron diaphragm (*D*) has its centre pulled more or less strongly towards *N*, so that *D* vibrates in exact unison with the variations in the current, and so with the diaphragm of the transmitter. The vibrations of *D* affect the air in contact with it, setting up waves which pass out of the opening in the lid, and these strike an ear applied to the opening, so that it receives practically the same sounds as struck the diaphragm of the transmitter.

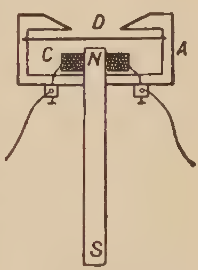


Fig. 88.

* *NS* is a magnet instead of soft iron, because it is found that *variations* of current have more effect on steel already magnetized than on soft iron; and the coil (*C*) is only wound round one end of *NS* instead of its whole length, because it is found that the response of a piece of steel to a magnetizing force is much more rapid when the force is applied at its ends than when it is distributed over its length.

143*. Measurement of the magnetizing effect of a solenoid on its core. In Experiment 27 the student assumed that the pole-strength induced in an iron bar in a weak magnetic field is proportional to the strength of that field; this is justifiable only so long as the magnetizing force is weak.

By means of a solenoid through which we can pass a current which can be varied at pleasure, we may produce in the iron core a magnetizing force similarly variable. This is due to the fact that the magnetic force inside a solenoid is directly proportional to the current flowing, provided no iron is present in the field of force. This can be proved by using a solenoid whose diameter is sufficient to admit an oscillating

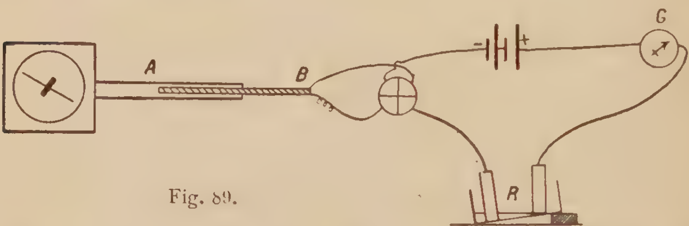


Fig. 89.

magnet as described on p. 30, by which the magnetic force inside can be directly measured.* It can be established less directly as follows.

EXPERIMENT 73. **Pole-strength of a solenoid with an air-core.** Take a straight solenoid about 40 cms. long, closely wound with insulated wire. Place it in the same position as the magnet *A B* in Fig. 26, so that the pole-strength at one end may be measured by the magnetometer as described in Experiment 20. The precautions taken in that experiment must of course be repeated.

Connect the solenoid to a commutator as in Fig. 89, and put the commutator in series with a tangent galvanometer or ammeter *G*, a battery such as one or two accumulators, and a variable resistance *R* (see Appendix, p. 290).

The tangent galvanometer must be put far away from *A B*, so that it is not affected by it.

Pass a current through *A B*, noting its magnitude as shown by *G*, and determine the deflection of the magnetometer-needle; the pole-strength of *A B* is proportional to the tangent of this angle.

* See Appendix A for a better method of performing this and the following experiments.

Vary the current by means of R, and find out whether the pole-strength is proportional to the current.

If this is so, the meaning of the result is that the magnetic force at the magnetometer produced by the current in the solenoid is proportional to the current: and the magnetic force at all points of the field will increase and decrease in the same proportion as at any one point of that field; so that the magnetic force inside $A\,B$ is proportional to the current.

EXPERIMENT 74. With the same arrangement as in the last experiment, insert a long soft-iron wire, about No. 10 gauge, into the coil, with one end at A, the other not reaching to B. Care must be taken that the solenoid is not disturbed during the experiment.

We are now in a position to measure the pole-strengths produced in this iron wire by a series of magnetizing forces, of which we do not know the actual strengths in absolute units, but which we can compare numerically, since they are proportional to the currents as shown by G.

If a series of observations is taken with continually increasing currents, it will be found that the pole-strength induced in the iron,* though proportional to the magnetizing force when that force is small, increases more slowly than the force when it becomes large, and finally ceases to increase, whatever increase is made in the current. The iron is then said to be magnetically **saturated.**

If the circuit is now broken without shaking the solenoid $A\,B$, the iron will not lose all its magnetism, but the least tap will destroy nearly all the **residual magnetization** if the iron is very soft.

EXPERIMENT 75. **Hysteresis.** With the same arrangement as in Experiment 74 gradually increase the current from zero to a value which approaches that necessary to saturate the iron, and then gradually decrease it down to zero again; then reverse the commutator and increase the current (now flowing through the coil in the opposite direction) to a maximum and decrease it to zero as before. The values of the deflection of the magnetometer (which should be read from time to time simultaneously with those of G) will show how the magnetism of the iron changes during a complete cycle of changes in the magnetizing force.

All these pairs of values should now be plotted on squared paper, taking as abscissae the values of the magnetizing current (in amperes, or simply tangents of the angles of deflection of the tangent

* Allowance must be made for the pole-strength of the solenoid.

galvanometer) and as ordinates the tangents of the angles of deflection of the magnetometer.

When the current is reversed, the abscissae must of course be measured off on the opposite side of the origin; and when the deflection of the magnetometer-needle passes through zero the same change must be made with the ordinates.

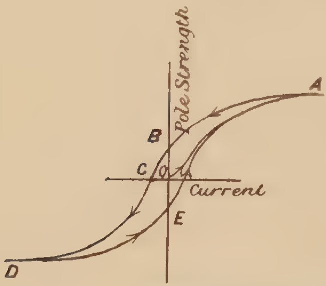


Fig. 90. Hysteresis Curve.

The resulting curve will be similar to Fig. 90, the arrows marking the order in which the points on the curve are produced during the changes of current above described.

If the changes in the current are continued for another cycle, the curve will rise from E to A again, not through O, but in a similar manner to the line BCD.

144*. In Experiment 75 it will have been seen that the magnetism of the iron 'lags behind' the magnetizing force; i.e. for the same value of the current there are two values of the magnetism of the iron, smaller or larger according as the current is increasing or decreasing. To this 'lagging' Prof. Ewing gave the name of **Hysteresis** (ὑστερέω, I lag behind).

The effect is much more pronounced in cast iron than in wrought iron, and much more so in glass-hard steel; compare the curve for steel got from the data given in Example 62 (p. 287).

For this reason, the core of an electro-magnet in which the magnetism is required to vary with the current must be made of soft iron; on the other hand, hard steel requires a fairly large demagnetizing force (OC, Fig. 90) to destroy its residual magnetism, and so is suitable for permanent magnets.

It can be shown that the *area* of the curve thus described is proportional to the energy that is needed to carry the magnetization of the bar through its cycle of changes; this energy is converted into heat and so is wasted, and consequently the core of the armature of a dynamo (p. 159) must be made of the softest possible iron, in order to avoid waste of energy and dangerous heating of the iron, for the area of the Hysteresis curve for soft iron is much less than that for steel.

CHAPTER XII

ELECTRODYNAMICS

145. IT was stated in Art. 133 that around a straight wire conveying an electric current there exists a magnetic field consisting of circular lines of force, which means that a N. pole near the wire, if free to move, would travel round and round it in a circle so long as the current flows. An ordinary magnet will not do this because it has also a S. pole, which tries to go in the opposite direction round the wire ; as a compromise the magnet will take up a position at right angles to the wire, as in Fig. 80.

146. Movement of a magnet-pole round a current. Faraday devised an arrangement wherein two bar-magnets were supported so that their N. poles could turn round a wire carrying a current. This current was led away from the middle of the magnets so that it did not flow along the part of the wire round which the S. poles of the magnet rotated. Thus he directly demonstrated the existence of circular lines of force round an electric current.

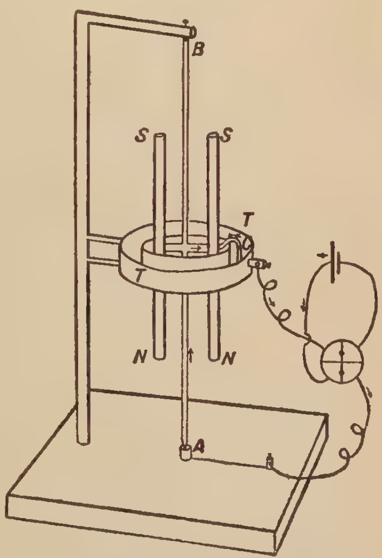


Fig. 91.

The principle will perhaps be understood from Fig. 91, where NS are the magnets, supported on a central rod AB, which can turn freely round a vertical axis. To the middle of NS a wire C is fixed, which dips into mercury in a circular horizontal trough TT. Thus C always dips in the mercury as NS turns round, and so connection is maintained between the binding screw on T and the rod BA. It is found that so long as a current passes as shown by the arrows, N

moves round the rod *AB*, and the motion is reversed when the current is made to flow in the opposite direction. The student should determine, with the help of the rule on p. 50, which of the two N. poles will begin to move out of the paper when the current flows as in Fig. 91.

147. Movement of a current-bearing conductor round a magnet-pole. By Newton's Third Law of Motion, action and reaction are equal and opposite, so that while the current urges the magnet-pole (N) round itself we may look on the magnet-pole as trying to make the current-bearing conductor move at the same time; and if we hold the pole fixed and support the current-bearing conductor in such a way that it can move, it ought to do so. Faraday arranged an experiment to show this, as follows (Fig. 92).

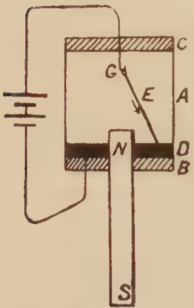


Fig. 92.

NS is a bar-magnet, A a short wide glass tube with corks B and C in its ends. D is mercury. E is a piece of wire loosely hung from a hook G, and dipping into the mercury. If a strong current is passed down this wire, as shown in Fig. 92, E will move round the magnet-pole N. Since in its present position, the current in it would tend to force N into the paper, E must begin by moving outwards from the paper.

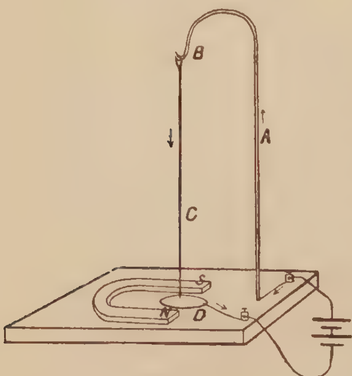


Fig. 93.

148. Movement of a current-bearing conductor across lines of magnetic force. It will be seen that the movement of the wire in the last article can be expressed by saying that it always tries to move so as to cut the lines of magnetic force at right angles, since these lines radiate from N (see p. 16). We can show this tendency in another way as follows.

In Fig. 93, A is a metal rod ending in a hook B, from which hangs

loosely a wire C, which dips into a pool (D) of mercury * in a hollow cut in the base-board.

A and D are connected to binding screws, and a current can be passed up or down C. If a horseshoe magnet is placed on the base-board as in the diagram, C will move until contact is broken by its leaving the mercury, when it will fall back, thus producing an intermittent motion.

If the current runs *down* C, we see by applying Maxwell's rule that it tries to force N to the left, and so is itself forced backwards to the right; simultaneously it tries to force S to the left, so on both accounts it is forced to the right.

149. It is much more scientific to consider the interaction of the current with the magnetic lines of force which cut the conductor rather than with various 'poles' at some distance away, the existence of which we only know through these external lines of force. Hence we will now drop the idea of current-bearing conductors moving round poles, and think of them as moving across lines of force. It will then be convenient to have a rule to find the direction of such movement; this is usually called **Ampère's rule**.

A man swimming with the current and looking along the lines of magnetic force in their positive direction, will be urged to his left.

In this rule, 'swimming with the current' means that he lies in and along the conductor with the current flowing from his heels to his head; and he must so turn himself as to look along the lines of force, in the direction in which a free N. pole would *move away* from him. For example, in Fig. 93, he would be diving downwards with the back of his head towards the spectator; his left hand would then be to the spectator's right.

150. Barlow's wheel. Barlow designed another apparatus to illustrate the tendency of a current-bearing conductor in a field of magnetic force to move at right angles to the lines of force; this is shown in Fig. 94, and consists of a metal disk turning on a horizontal axis. The disk is cut into a series of spokes which dip into a pool of mercury, and if a current passes along the spoke which happens to be in the mercury, while a horseshoe magnet is put so that its lines of force are at right angles to the spoke, the wheel will spin round.

* Mercury is convenient for this purpose, both because it forms an excellent flexible conductor and because it can be made to stand in a drop so that its surface is higher than the board, thus providing clearance for the wire C.

The student should determine, by the application of Ampère's rule, whether the rotation of the disk in Fig. 94 is 'clockwise' or the reverse.

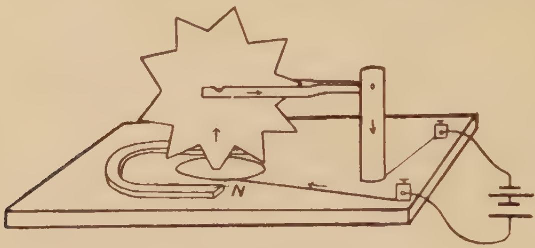


Fig. 94. Barlow's Wheel.

This forms the simplest type of Electromotor: it is of course extremely inefficient, but its principle of action is the same as that of large continuous-current motors.

151. Electromotor. Suppose we have a wire rectangle *A B C D* carrying an electric current and free to move round a horizontal axis through its centre in its own plane. Let it be placed in the middle of the space between the N. and S. poles of a magnet as in Fig. 95.

If the current is flowing from *A* to *B*, it will be seen by Ampère's

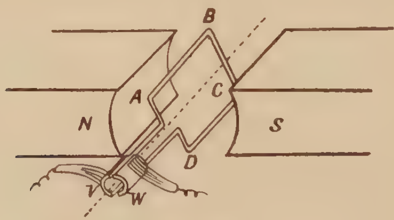


Fig. 95.

rule on p. 143, that the wire *A B* will tend to move across the lines of force, so that *A B* moves 'counter-clockwise' across the face of *N*. At the same time, since the current flows from *C* to *D*, *C D* will by the same rule be seen to tend to move upwards across the face of *S*. Hence the rectangle will turn till *C D* comes to the top, and *A B* to the bottom.

If the current continues to flow the same way round the rectangle,

no further motion will occur, since the current in 'the top piece of wire' is now flowing towards the spectator.

If, however, the direction of the current in the wire rectangle is reversed at this point, so that it again flows in the top wire from the spectator, the rectangle will move in the same direction as before; and this motion will continue, provided that the direction of the current in the rectangle is reversed each time the wire reaches the top and is maintained in that direction until it reaches the bottom.

This reversal can be effected automatically if the wire rectangle terminates in a split-tube, as *V*, *W* in Fig. 95, with two fixed metal tongues or 'brushes' pressing against it. These brushes are so placed that the two gaps in the tube pass the two brushes as the wire rectangle becomes vertical; if an electric current from a battery is sent into the rectangle by one brush and out by the other, the wire rectangle will tend to spin round, automatically reversing the current in itself at the required point of each revolution. This reversing arrangement is called a **Commutator**, and the whole an **Electromotor**.

152. The turning effort is directly proportional to the number of lines of force cut by the coil, so that it will be largely increased if the space between *N* and *S* is nearly filled by a block of soft iron (see Fig. 23). This can be effected by winding the wire rectangle on an iron cylinder, which turns with the wire.

The effect is also increased by using more than one rectangle of wire, as in a galvanometer, making a coil whose ends are connected to the two parts of the commutator. Such a coil, mounted on its iron core, is termed the '**Armature.**'

In practice, since an electro-magnet can be made much stronger than a permanent magnet, *N* and *S* are the pole pieces of an electro-magnet, which is excited by passing through its coils the same current as passes through the armature.

The turning effort or 'torque' of such a motor is somewhat variable throughout its revolution, and to obtain smooth running it is usual to have the armature wound with a number of coils, and the commutator with a corresponding number of sections, as described in the dynamo (p. 158).

The difficulties, due to hysteresis, the magnetizing effect of armature currents, eddy currents, &c., which occur in the dynamo are met with in a motor, and overcome in the same manner; in fact, the same machine can be used either as a dynamo or a motor, according as it is supplied with mechanical or electrical energy.

153. D'Arsonval galvanometer. The moving coil galvanometer described in Art. 81 *a* is an example of the use of the mechanical force experienced by a current-bearing conductor in a magnetic field.

The chief advantages of such a galvanometer are two. First, it is unaffected by the presence of neighbouring magnets, since the field of force in which the coil hangs is so intense that any modification by outside magnetic influence is inappreciable; hence it may be used even among dynamos, &c., without inconvenience, and its reduction factor does not depend on H.

Second, it is practically 'dead beat,' i. e. on the passage of a current, instead of oscillating about, and slowly settling down at, its new position, the coil goes to its final point and stops there, after perhaps one or, at most, two oscillations. This makes the operation very much more rapid. When the coil moves across lines of force, 'eddy currents' are produced which tend to check the motion (see p. 155). Since they are only caused by the movement of the coil they cannot exercise a permanent effect in keeping the coil out of its proper position, as may happen through the friction of the pivot in a compass-needle supported on a point.

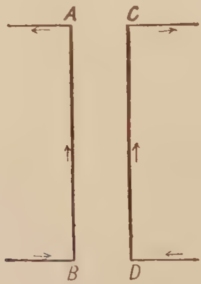


Fig. 97.

154*. Attraction and repulsion of parallel currents. Suppose $A\,B$, $C\,D$ in Fig. 97 are parts of the same or different circuits through which currents are flowing. Then each is surrounded by its own field of magnetic force. Consider that produced by the current in $A\,B$, supposed to be flowing upwards. In the neighbourhood of

CD the magnetic field due to AB consists of lines going straight into the paper. The current-bearing conductor CD will then tend to move at right angles to these lines of force, and if Ampère's rule is applied it will be seen that the movement will be to the left, or towards AB. If AB be considered as a current-bearing conductor in the field of CD, it will be seen to be urged towards CD. Thus two wires side by side in which currents are flowing in the *same* direction are attracted together.

In the same way, it can easily be shown that if the currents are in opposite directions, repulsion occurs.

These facts were discovered experimentally by Ampère, who arranged a stand, as in Fig. 98, whereby one of the current-bearing conductors was allowed free movement.

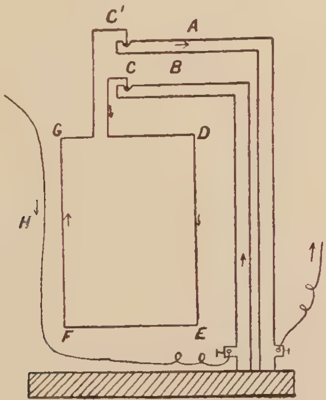


Fig. 98. Ampère's Stand.

155*. In Fig. 98 a wire frame $CDEFGC'$ is supported on a couple of metal rods A and B by two cups C and C' filled with mercury; the frame can thus turn round a vertical axis through CC'. If the wire H, by which the current comes to B, be put parallel to and near to FG, or DC, the action between two parallel current-bearing conductors can be observed, both for like and unlike currents.

If a solenoid is made so that the ends of the wire can dip in C and C', supporting the solenoid in a horizontal position, its similarity to a magnet while carrying a current will be seen, since it will be attracted

or repelled by a magnet-pole, and will slowly move towards the meridian if left to the action of the earth's field alone.

156. If the results stated in this chapter as to the movements of current-bearing conductors in a magnetic field are grouped together, it will be seen that they all fall under the following generalization. The conductors composing a closed circuit situated in an external magnetic field of force tend to change their position so as to cause the maximum number of lines of force to pass through the circuit in the same direction as those due to the current in the circuit. If we define the latter as the 'positive direction' for lines of force with respect to the current, we may put it briefly thus: **A circuit carrying a current tends to embrace as many lines of force as possible passing through it in the positive direction.**

CHAPTER XIII

Induction of Currents

157. If a moderately sensitive galvanometer is connected in series with a coil of wire (no cell being included in the circuit) and one pole of a bar-magnet is rapidly thrust into the coil, the galvanometer-needle will be seen to be deflected; the galvanometer, of course, must be placed so far from the coil that it is not affected by this movement of the magnet unless the above circuit is closed. This current is only momentary, ceasing with the movement of the magnet-pole; but if the magnet is rapidly withdrawn, a current in the opposite direction will be indicated by the galvanometer.

These currents are called 'induced currents'; they were discovered by Faraday in 1831.

Since, for all external points, a magnet-pole is merely the origin of a number of lines of magnetic force, it would seem that this induction of a current must be caused by the passage of some lines of force across the wires forming the closed circuit. The experiment can be simplified in this direction as follows. Take a delicate

galvanometer of low resistance, and connect its binding screws together by a piece of copper wire two or three metres long; move a single straight piece of this wire between the poles of a strong horse-shoe-magnet (so that it cuts across the lines of force between the poles), and a momentary current will be shown by the galvanometer.

If, in the pieces of apparatus described in Articles 146, 147, 148, 150, and 151 of Chapter XII, a galvanometer is substituted for the battery, and the movements which took place in consequence of the current from that battery are *forced* to take place by hand, in each case a current will be indicated by the galvanometer. This current will be in the opposite direction to that which would have produced the movement. As long as the instrument is at rest no current is induced; the more rapid the movements, the stronger are the induced currents.

158. To revert to the experiment with which we began, the same effect will be produced if, instead of a permanent magnet, we use an electro-magnet, consisting of a coil of wire, conveying a current, wound round an iron bar.

Again, the change which induces the current is from the state of things in which the magnet is outside the coil to that in which it is inside. We might then expect (as is the case) that a current will be induced in a coil if an electro-magnet is *created* inside it. This can be done by sending a current round a coil with an iron core, already inside the former coil but not in electrical contact with it. A current in the reverse direction will be induced in the outer coil when the current in the inner coil is stopped, since this is equivalent to the withdrawal of the magnet; but as before the induced currents are only momentary, and do not flow steadily, although the current in the inner coil may do so.

The same effects will occur, though of course to a much smaller extent, if the electro-magnet lacks an iron core.

159. We may think of the result of passing a current through a solenoid as being the production of a number of lines of magnetic force linked with the solenoid, which start out from the solenoid when the current is made to flow, remain in their places while the current is flowing, and close in on it again when the current stops. These lines of force necessarily cut across the wires of an outer coil embracing the former as they go out and come in, and so induce

a current in the outer coil if it forms part of a separate closed circuit (Fig. 99).

In this diagram *A A* represents a section of the inner coil connected to a battery *E* and key *K*; *B* the section of the outer coil of many turns of wire connected to a galvanometer *G*. The lines of magnetic force are indicated, linked through both the coil which produces them and the outer coil *B*.

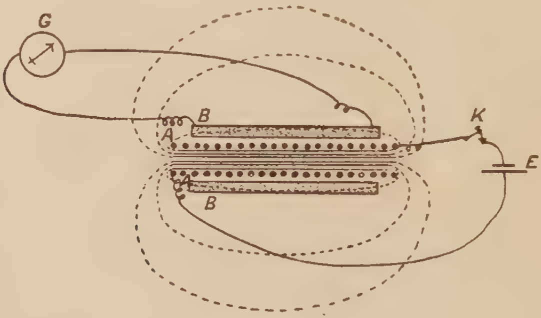


Fig. 99.

It will be seen that it is not necessary that the coil in which the current is started and stopped should be inside the coil in which the current is to be induced; provided that the lines of force due to the first cut through the second coil, a change of current in the first will induce a current in the second. If, for example, the coils are such as are used in a tangent galvanometer, and placed with their planes parallel to one another, a change of current in one will induce a current in the other; but if they are put so that the plane of one passes through the centre of the other at right angles to its plane, then no induction will occur.

160*. Fundamental law of current-induction. The following law represents the result of experiments made on the induction of currents. In it a 'line of magnetic force' is supposed not only to have a definite position and direction in space (i. e. the direction in which a free N. pole tends to move), but also to represent the magnitude of the magnetic force intensity at the point, by the number of such lines per sq. cm.; and the 'positive direction round a circuit,' through which passes a line of force, is related to the positive direction of the line of force in the same way as the movements of rotation and translation in a corkscrew. For example, if the circuit (Fig. 100) is in the plane of the paper, and the line of force runs from the spectator, the positive direction round the circuit is *A C B*; but if the direction is towards the spectator it will be *A B C*.

The law is *decrease, or, increase, in the number of lines of magnetic force which pass through a closed circuit induces a current round the circuit in the positive, or negative, direction respectively; and the total E.M.F.* is equal to the rate of decrease in the number of lines which pass through the circuit.*

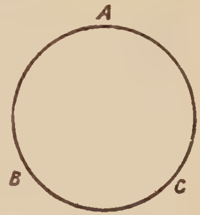


Fig. 100.

If the circuit is so arranged, as in a solenoid for example, that each line of force cuts the circuit several times, this counts as an equal number of lines added or subtracted, hence the greater the number of turns in the outer coil the higher will be the induced E.M.F., for each line of force generated by the inner coil. If we take an enormous number of turns in the outer coil, a very high E.M.F. may be induced in it, by breaking in the inner coil a current produced by only two or three cells; this is the principle of the induction coil, first made in a practical form by Ruhmkorff.

161. Ruhmkorff's, or Induction, Coil. The induction coil consists of a bar of soft iron wound with a single layer of thick insulated wire called the 'primary coil.' Over this is wound a coil of many thousands of turns of very thin, well-insulated wire, called the 'secondary coil.' The ends of the wire forming the secondary coil are brought out to a couple of very well insulated binding screws, with which are usually connected two adjustable metal rods ending in points between which sparks can pass. In circuit with the primary coil is a battery, usually of from one to four storage cells, and an automatic arrangement for making and breaking the current, exactly as in an electric bell (p. 133).

The coil is mounted on a box containing a 'condenser,' the action of which will be explained later (p. 153). It consists of a number of sheets of tin-foil and paraffined paper laid on one another, alternate sheets of tin-foil being connected into two groups.

A commutator is usually included in the primary circuit.

The connections are shown in Fig. 101, but the student will not understand the apparatus without examining an actual coil in action. *A* is the central iron core, which is made of a bundle of iron wires to avoid 'eddy currents' (p. 155). *B* is the primary and *C* the secondary coil. *D* represents the pointed discharging rods. *E* is a block of soft iron which is attracted to *A* when the current flows in the primary. This is mounted on a spring *F*, fixed to a block *G*.

* It must be remembered that in this law the E.M.F. is measured in absolute electro-magnetic units (see Art. 108), of which 100,000,000 go to the volt.

Under ordinary circumstances E is held by the spring in contact with a screw H, which passes through a brass block J; when E is attracted to A the primary circuit is broken between H and E *. The condenser C' is connected to G and J and forms a kind of shunt (Art. 116) to the gap between H and E. K is the commutator and L the battery.

When contact is made at the commutator K, A becomes powerfully magnetized and attracts E, thus breaking the primary circuit. The stoppage of the current is very sudden, and since the secondary

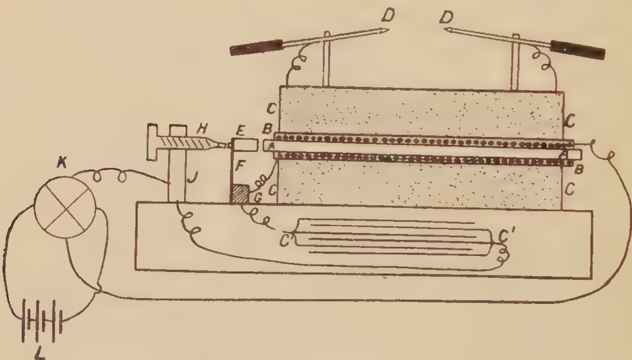


Fig. 101. Ruhmkorff Coil.

coil contains an enormous number of turns, the many lines of force due to A pass through the secondary circuit at great speed, and so induce a high E.M.F., which may amount to hundreds of thousands of volts. Such an E.M.F. between the ends of the discharger is able to break down the insulation of the air, and a spark passes between them. An E.M.F. of about 50,000 volts gives a 1-inch spark; a 10-inch spark such as is commonly used for producing Röntgen rays needs about 300,000 volts; and the most powerful coil ever made, which gave sparks 3 feet 6 inches long, probably produced a million volts.

When the block E is carried back to H by the spring F, the current again flows in the primary, but by means of the condenser the rate of re-establishment of the current is made comparatively

* The points of contact on H and E are armed with platinum to lessen the destructive action of the 'spark at break' (see p. 155).

slow, so that the induced E.M.F. at the 'make' of the current is very much less than that at 'break,' and if the points of the discharger *D* are set for the spark at break, the reverse spark is not able to pass. Thus a spark occurs every time the primary current is broken.

162*. The condenser. The student who has read Part III will understand the condenser to be similar to a battery of Leyden jars, in which the dielectric is very thin and the coated area very large, so that its capacity is considerable. To one who has yet to read that Part, it may be explained as a kind of reservoir, or pair of reservoirs, into which electricity can flow.

When the current is broken at the point *H*, if no condenser existed there would be a bright spark, caused by the current persisting after *H* and *E* have separated, due to 'self-induction' (see p. 154). This gradual decrease of the primary current would impair the suddenness of the break and therefore lessen the induced E.M.F. of the secondary. When however a condenser is connected, as in Fig. 101, this current flows into and charges the condenser; by the time this has been done the block *E* will have moved away from *H* so that the current cannot leap across the gap, and the current in the primary stops almost instantaneously.

Now the E.M.F. of this momentary current of self-induction is very high, so that the condenser is greatly overcharged, and the electricity which has flowed into it surges out again backwards through the primary, so setting up a kind of reverse current and rendering the break more complete; and if the rapidity of vibration of *E* is correctly timed (or 'tuned' to the condenser) so that the primary circuit is remade before this has disappeared, the flow of the ordinary direct current in the primary will be retarded, and its rate of growth, already impeded by the effects of its own self-induction, will be decreased. Thus the E.M.F. induced in the secondary at 'make' is very much less than at 'break,' and the secondary current instead of being an alternate current is an intermittent high potential current in one direction only.

163. Uses of an induction coil. A Ruhmkorff coil is of considerable practical use; instances of this are, in the production of Röntgen rays (see p. 187), in wireless telegraphy (see p. 191), and in producing the spark which ignites the mixture of air and gas in the oil-engine of a motor-car.

164*. Self-induction. We have seen (Art. 159) that, if two circuits lie side by side, any change in a current flowing through one of them induces a momentary current in the other.

Suppose $A\,B\,C$, $D\,E\,K$ are such circuits seen from above, E being a battery, and K a tapping-key.

When K is depressed, suppose a current is sent by E in the direction $E\,K\,D$. This will cause lines of force, passing downwards (see p. 50) through both circuits; with respect to these lines the positive direction round the upper circuit is $A\,B\,C$. When the circuit $E\,K\,D$ is closed, the number of lines through $A\,B\,C$ is *increased*, therefore, by the law on p. 151, the induced E.M.F. round $A\,B\,C$ is in the *negative* direction, i.e. the current will flow in the direction $C\,B\,A$.

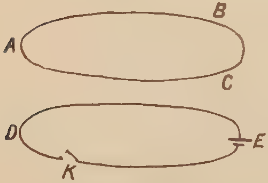


Fig. 102.

Now imagine that $A\,B\,C$, $D\,E\,K$ are consecutive turns of a spiral as in Fig. 103, the spiral having many turns and the ends being connected together. If now K is depressed so that the battery tries to send a current in the direction $D\,E\,K$, this current will induce in the next turn an E.M.F. in the direction $C\,B\,A$, i.e. in a direction opposite to that in which the battery is sending the current. Thus the growth of the current in a spiral is retarded by the induction of each turn on the next, and, in a less degree, on all the others. The effect will be enormously increased if an iron rod is put in the spiral; so that in an electro-magnet the current produced by a battery does not at once rise to its full strength.

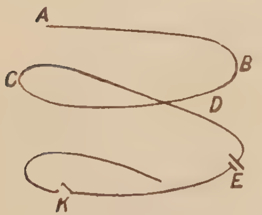


Fig. 103.

In exactly the same way it may be seen that when the current in a spiral is flowing steadily, and the circuit is broken at any point, the cessation of current in one turn induces a *forward* E.M.F. in the others, i.e. an E.M.F. which tends to maintain the flow of the current. These effects are called *self-induction.*

If the number of lines of magnetic force produced by the current in the spiral is large, this E.M.F. is large enough to break down the resistance offered by the air in the newly-made gap, and a spark passes at the point where contact is broken. This is the reason why a spark is often seen

when a circuit carrying a current is broken, more especially if an electro-magnet is included in the circuit, as in the electric bell and induction coil. The E.M.F. of a single accumulator may be exalted by the self-induction of an electro-magnet in circuit with it, sufficiently to send a momentary current through the great resistance of the human body, as may be tested by holding in each hand one of the wires on each side of the point where contact is broken. The simplest way to see this 'spark at break' is to attach a file to one of the poles of a cell, and rub the end of a copper wire connected to the other pole along the file; the steel of the file where contact is broken is ignited by the spark. It is in this way that the arc in an arc lamp is 'struck' (see p. 179).

165. Lenz's law. In 1834 Lenz summed up the phenomena we have described above, with the help of the relations which (see Chapter XII) hold between currents and the movements they tend to produce, in one general law, which may be stated as follows.

If a conductor forming part of a closed circuit be moved in a magnetic field, or if the field undergo a change of strength, then during the movement or change the conductor is traversed by a current whose electro-magnetic effect is to oppose the movement of the conductor or the change of the field.

It may be put more briefly thus :—

In all cases of electro-magnetic induction the induced currents tend to stop the change which produces them.

166. Eddy currents. Hitherto we have considered the currents induced in a wire by its movement relative to lines of magnetic force, but of course the same will happen if we move a solid conductor, such as a mass of copper, in a magnetic field. The currents so produced do not flow in a clearly defined path, but in 'eddies.'

These induced currents will tend to stop the relative motion, and this check to the motion of a solid conductor near a powerful magnet can easily be demonstrated.

Thus, if a thick sheet of copper be 'sawed' up and down between the pole-pieces of a powerful electro-magnet, no opposition to the motion can be perceived until the current is turned on, and even then not unless the motion is rapid. Faraday showed this (and the experiment can easily be repeated) by hanging a copper cube (or sphere) by a thread between the pole-pieces, and twisting the thread so that when released the cube spun round. When the electro-

magnet was excited the motion almost ceased; it was as if the cube was suddenly surrounded by a very viscous liquid. Of course the motion does not entirely stop, since there would then be no currents induced and therefore nothing to stop the motion.

The 'damping' effect of eddy currents is often used, e.g. in the moving coil galvanometer, electric light meters, some speedometers of motor cars, &c.

These eddy currents may be very undesirable, as in the armature-core of a dynamo or motor (see p. 159).

167. The dynamo. The first machine for the mechanical production of an electric current was made by Faraday in 1831; it practically consisted of Barlow's wheel (p. 144) driven by hand, as described on p. 149. Improvements were rapidly introduced; in 1833 a bobbin of insulated wire was substituted for a disk, in 1846 a commutator was added to keep the current in the external circuit in the same direction, in 1856 Siemens introduced the very great improvement of an iron core to the armature; with the substitution of an electro-magnet for a permanent magnet, and the introduction of a number of coils in the armature, the machine attained nearly to its present form.

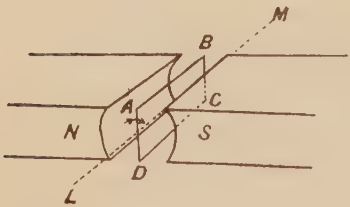


Fig. 104.

We have seen (p. 149) that when a wire is made to move so as to cut across lines of force, a current is produced in the wire. Let the wire be bent into a closed rectangle $ABCD$ (Fig. 104). Let this rectangle be movable about an axis (LM) through its centre, between the poles of a magnet (NS). The parts AD, BC of the wire will not cut lines of force and so have no E.M.F. induced in them, but if DA moves 'clockwise,' the number of lines of force from left to right in the rectangle is being decreased, so that an E.M.F. in the direction $BADC$ will be induced round the coil. This goes on until the rectangle is horizontal, i.e. through an angle of 90°, when there are *no* lines of force through the wire rectangle.

If the rotation continues, the number of lines of force through the coil from left to right will increase, but the coil now turns its other face to the lines, so that viewing the coil along the lines of force, i.e. from

N, the E.M.F. will now be counter-clockwise, i.e. along $D\ C\ B\ A$, or actually in the original direction round the coil. This will continue until the wire is again vertical.

Thus through one half turn there will be a current induced in the coil flowing toward the spectator along $B\ A$, and from him along $D\ C$.

If the rotation continues, $A\ B$ and $D\ C$ having now exchanged places, a current will be induced during a half turn flowing towards the spectator along $C\ D$, and from him along $A\ B$, i.e. in the opposite direction to its flow in the first half turn.

Thus, as the rectangle is spun round, an alternating current traverses the rectangle.

If the circuit is broken and attached to two rings ($E\ F$, Fig. 105) mounted on the axis ($L\ M$), and metal 'brushes' (G, H) are made to touch these rings, the current will be led away through any external circuit (X) connected to the brushes. X may, for example, include a glow-lamp. The current in X will be reversed twice in every revolution of $A\ B\ C\ D$.

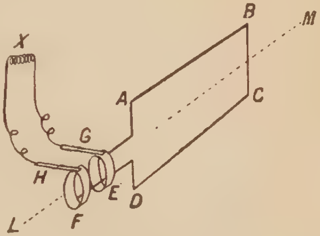


Fig. 105.

If the external circuit (X) is not complete, so that no currents are induced in the rectangle, it will be found that less force is needed to turn the rectangle, since induced currents oppose the motion, by Lenz's law (see p. 155).

168. Commutator. If, however, the ends of the coil are brought out to a split-tube ($V\ W$, Fig. 95), and the brushes are so placed that they touch at opposite points of the tube, and so that the gaps pass under them as the wire rectangle passes the vertical position, then the current in a circuit connected to these brushes will always be in the same direction; it will, however, vary in strength from zero to its full value.

169. Iron core to armature. With such a large gap between N and S, the field cannot be made very intense, but if the wire rectangle (or 'armature') is wound round an iron cylinder the number of lines of force cut by the wire, and consequently the induced E.M.F., will be greatly increased.

170*. Ring armature. The armature we have described, consisting of a coil wound on the surface of an iron cylinder or drum, is called a 'drum armature'; another method is very commonly adopted, in which the coils are wound round a ring. It may be represented diagrammatically by Fig. 106, in which the thick line represents the

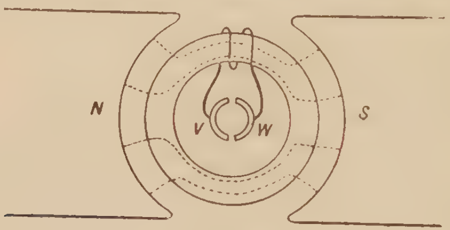


Fig. 106.

wire wound in a coil on the iron ring, through which pass the lines of force from N. to S.; *V*, *W* is the commutator as before. It will be seen that as the ring turns through 180°, the number of lines through the ring decreases from its full value to zero, and increases in the opposite direction to its full value again, so that as before an E.M.F. will be induced in it.

With this form, too, the E.M.F. in the external circuit will be always

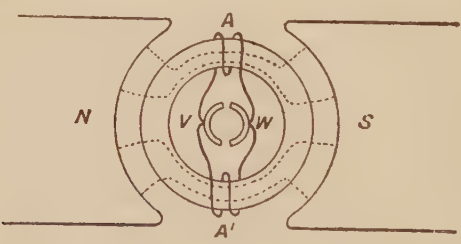


Fig. 107.

in one direction, but variable between zero and its full value. This latter difficulty can be overcome by winding on the core a larger number of coils, and bringing their ends to a commutator containing a corresponding number of sections.

In the first place it can be seen that in Fig. 107 the addition of the coil *A'* to the commutator helps the effect of *A*, since the E.M.F. in

both tends to send current towards *W*, if the ring moves clockwise; the coils *A* and *A′* act like two cells in parallel.

Fig. 108 shows a four-part commutator with four coils on the armature-core. It will be seen that these form a practically continuous coil round the core, from which wires run to the sections of the commutator. In any one position, of course, only two sections of the commutator

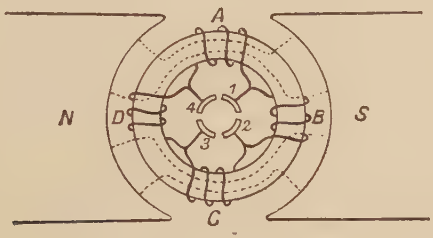


Fig. 108. Ring Armature.

are in contact with the brushes, the others being idle, so that *A B C* acts as one coil in which the E.M.F. is throughout in one direction (towards *C*), and *A D C* is in parallel with it. Thus, if the brushes always touch the 'north-west' and 'south-east' sections of the commutator, there will be an E.M.F. between them which fluctuates four times per revolution, but never sinks to zero.

In large machines there are thirty or forty such sections.

171. Eddy currents. Currents will be induced in the material of the armature-core, just as in the wires, and these cause a waste of energy, since they oppose the movement of the armature, by Lenz's law. They are reduced to a minimum by 'laminating' the core, i.e. building it up of 'leaves' of sheet-iron so arranged that the sheets lie at right angles to the induced E.M.F., that is, to the wires of the armature. Thus the core is composed of a number of disks strung on the driving axle. These sheets are varnished before being put together, to prevent the current passing from one to another.

172*. Hysteresis. As the iron core of the armature turns round, the magnetization in it induced by the magnets is continually changing its direction. The 'lag' of the magnetization behind the magnetizing force, i.e. the hysteresis (see p. 140), involves a loss of energy; this can be reduced by making the core of very soft iron.

173. Field-magnets. The electro-magnets which produce the magnetic field are, in continuous-current machines, supplied with current from the armature itself. It may seem difficult to understand how the current ever begins, since it produces the magnetic field and is itself produced thereby; but there is always a little permanent magnetization in the field-magnets which starts a small current, this strengthens the field-magnets, and so on.

Sometimes the whole of the armature current passes round the field-

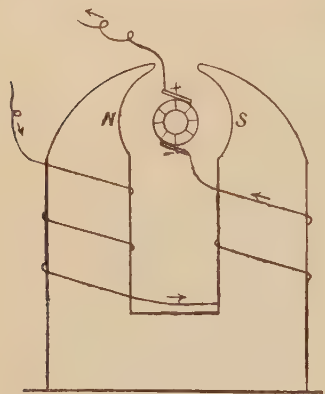


Fig. 109. Series.

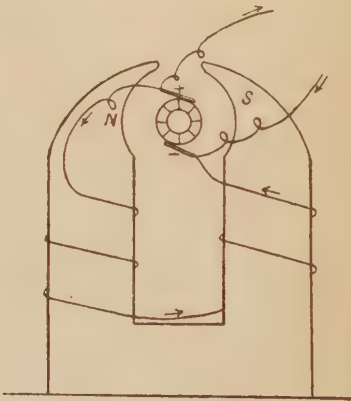


Fig. 110. Shunt.

magnets, which are then wound with a few turns of thick wire, and the dynamo is then said to be **series-wound**, as in Fig. 109. Sometimes the coils of the field-magnets form a shunt to the external circuit, and the dynamo is then **shunt-wound**, as in Fig. 110.

In spite of the loss of energy involved in driving current through the field-magnet coils, and in hysteresis, eddy currents, &c., a large modern dynamo will give back as electrical energy more than 90 per cent. of the energy supplied to it by the driving engine.

CHAPTER XIV

Electrolysis

174. In this chapter the student will be assumed to possess some acquaintance with elementary inorganic chemistry.

It was seen in Experiment 49 that when an electric current passes

through a solution of copper sulphate as part of the conducting circuit, the end of the wire by which the current leaves the liquid becomes coated with copper.

If we attempt to pass a current in a similar manner through petroleum or turpentine or one of many such liquids, we shall fail, these liquids being insulators.

If we attempt to pass a current through mercury or any other melted metal, we shall find no difficulty in doing so; but no effect will be produced in the mercury (except that it gets warmer, as happens with all conductors carrying a current, see Chapter XV) or on the wires by which the current enters or leaves the liquid.

If we attempt to pass a current through a solution of a salt such as copper sulphate or silver nitrate, or an acid such as hydrochloric, or a fluid compound such as lead chloride in a melted condition, we shall find that as long as the current flows, chemical action takes place at the points of entry and exit of the current. This is called *Electrolysis*.

175. Electrolysis of water. We will first consider the electrolysis of water. Suppose we have a vessel of perfectly pure distilled water, with two platinum plates (A, B) immersed in the water as in Fig. 111, and that by means of a battery we force a current through the water from A to B; then bubbles of gas will rise from each platinum plate, and may be collected in tubes (C and D) filled with water and inverted over the plates. These gases will be found to be, in C pure oxygen (with a little ozone, which is an 'allotropic' form of oxygen), and in D pure hydrogen; and however long the action continues the volume of hydrogen produced will be very nearly double that of the oxygen. These gases only appear at A and B; no change is visible in the liquid between them, except diminution of quantity.

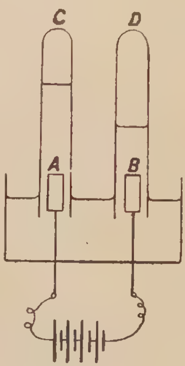


Fig. 111.

As a matter of practice the resistance of pure water is so enormous that the experiment would take years; it is customary to add a large proportion of something, such as sulphuric acid, which reduces this resistance enough to allow a large current to pass, when the same result happens. What is the rôle of this sulphuric acid is not known with certainty, but we

will assume for simplicity that time is no object and the experiment is made as described above.

176. For convenience the following names have been given. *Electrolysis** is 'the process of splitting up a liquid chemically by passing an electric current through it'; the liquid is called an *electrolyte*. The solid conductor by which the current enters the liquid is called *anode* (ἀνά, up, ὁδός, the way), and that by which it leaves it, the *cathode* (κατά, down, ὁδός, the way); these two are also called *electrodes*.

We may then say that when water, or dilute sulphuric acid, is electrolysed, with platinum electrodes, oxygen appears at the anode and hydrogen at the cathode.

177. Electrolysis of hydrochloric acid. In the same way a concentrated solution of hydrochloric acid may be electrolysed, and hydrogen will appear at the cathode, while chlorine will appear at the anode. Since the chlorine so evolved will attack platinum, the anode must be made of carbon; and since chlorine is exceedingly soluble, the liquid must be saturated with common salt and the current passed for some hours, so that it may take up as much chlorine as it will. It will then be found that chlorine is produced at the anode at exactly the same rate, volume for volume, as the hydrogen at the cathode.

178. In the case of both water and hydrochloric acid the products of electrolysis are capable of re-combining, in the same proportions as they appear, to form the respective electrolytes, so that there is a direct splitting up of the compound into simpler materials, which go each to its own electrode. These materials are called *ions*†, and that going to the anode is called the *anion*, that going to the cathode the *cation*. In the above cases oxygen and chlorine are anions, and hydrogen is the cation.

In the majority of cases, however, these ions on reaching their electrode give rise to chemical action with the electrode, with the solvent or with something else present in solution, so that the substance that appears at the electrode is not the direct result of the action of the current on the electrolyte. We will now consider one or two cases of this 'secondary' action.

179. Electrolysis of copper sulphate. If a solution of copper sulphate is electrolysed between platinum electrodes, copper

* From λύω, I loose. † From ἰών, going.

will be deposited on the cathode, and oxygen will appear at the anode. The chemical composition of copper sulphate is represented by the formula $CuSO_4$, so that it might be expected that if the cation is Cu, the anion would be SO_4 (sulphion, as it is called). No chemical compound of this composition has ever been obtained; there is one represented by SO_2, and one by SO_3, so that we should expect one of these to appear, with oxygen. This, however, does not happen, but the 'sulphion' seems to enter into combination with some of the water at the anode (whose composition is shown by H_2O), displacing the oxygen and so forming sulphuric acid (H_2SO_4).

Thus the results of electrolysis at the anode are that oxygen bubbles appear and sulphuric acid is formed there, but is only slowly apparent through the changing colour of the solution and its acid reaction.

If, however, the anode is made of copper instead of platinum, the sulphion attacks this instead of the solvent, and forms with it copper sulphate ($CuSO_4$), so that no results of electrolysis are apparent at the anode; the anode decreases and the cathode increases in size (see Experiment 49).

180. Electrolysis of sodium sulphate. If a solution of sodium sulphate is electrolysed between platinum electrodes, oxygen will be disengaged at the anode and hydrogen at the cathode; and if to the solution is added a little neutral litmus this will be seen to become red at the anode and blue at the cathode. Sodium sulphate is represented by the formula Na_2SO_4, so that the ions are sodium and sulphion; as before, the latter by acting on the water gives rise to free oxygen and sulphuric acid at the anode, and the sodium ion interacts with the water at the cathode, producing free hydrogen and a solution of sodium hydrate. Thus we have a secondary action at both electrodes.

181. Quantitative results. Faraday made a series of careful experiments to discover the relation between the quantities of the substances set free at the electrodes. The results of some of these have been mentioned on p. 73. He also found that if voltameters (or electrolytic cells) containing the same electrolyte are introduced at different points of a single circuit, the same amount of electrolyte is decomposed in each, showing that the same quantity of electricity (as defined on p. 103) is flowing past each point of a circuit at the same

time; i.e. that the introduction of a resistance in a circuit lessens the current from the battery instead of absorbing part of it in its passage. This is often spoken of as Faraday's First Law, and may be stated thus:—

The amount of chemical action is the same at all points of a circuit.

He also made a current pass through a series of voltameters with different electrolytes and different electrodes. Where the product of electrolysis in two of these cells was the same (e.g. hydrogen at the cathodes of cells containing acidulated water, hydrochloric acid, or sodium sulphate solution), he found that the weight of this substance liberated in each of the cells was the same. Now in each cell the substances appear at the electrodes in chemically equivalent quantities (e.g. two volumes of hydrogen to one of oxygen), hence he was led to the following law:—

When a current passes through different electrolytes in series the ratio between the quantities of the substances appearing at the electrodes is the same as that of their chemical equivalents.

This may be called Faraday's Second Law; it may be made clearer by a definite example.

Suppose that a current passes through two cells in series containing respectively (A) acidulated water, (B) copper sulphate solution, both with platinum electrodes, and a third (C) containing copper sulphate solution with copper electrodes. Suppose that the current is allowed to flow until 1 grm. of hydrogen has been liberated in A. To form the water in A, 8 grms. of oxygen are combined with each grm. of hydrogen, so that 8 grms. of oxygen are liberated at the anode in A, and therefore also at the anode in B. Now 31·6 grms. of copper are chemically equivalent to 8 grms. of oxygen, so that 31·6 grms. of copper will be deposited on the cathode in B, and therefore also in C.

Thus, from Faraday's results, we see that the following quantities are simultaneously liberated. Hydrogen 1, oxygen 8, copper 31·6.

These numbers are the chemical equivalents of these elements.

The student must bear in mind the fact that the chemical equivalent of an element may depend on its valency in the compound containing it. Thus copper in the cupric sulphate mentioned above is divalent, but in cuprous chloride it is monovalent. If, then, a voltameter (D) with carbon anode, containing cuprous chloride dissolved in hydrochloric acid, is added to the above

series, while 1 grm. of hydrogen is being liberated in *A*, and 31·6 grms. of copper deposited in *B* and *C*, we shall get 63·2 grms. of copper deposited in *D*. The student should calculate the weight of chlorine liberated in *D*.

182. A third law of electrolysis is frequently stated, on the assumption that the magnitude of an electric current is defined and measured by means of its *electro-magnetic* power; i. e. by its effect in producing a magnetic force at the centre of a coil in which it flows. This is not the course which we have adopted, the magnitude of a current being defined and measured by the amount of copper it will deposit per second (p. 73). On p. 81 it was stated that Faraday investigated the connection between these electro-magnetic and electrolytic effects of a current, with results which amount to the third law above mentioned; it may be stated thus:—

The strength of a current, if measured electro-magnetically, is proportional to the amount of a substance liberated at an electrode in a given time.

This law, however, does not naturally come here, but in a discussion of the galvanometer, if the current is defined as in Chapter VI.

183. Resistance of an electrolyte. Experiment 73 was an example of a rough method of measuring the resistance of an electrolyte; it would be found that the resistance diminished with a rise in temperature of the cell. This decrease in resistance of an electrolyte with the temperature † is the opposite to the behaviour of a metallic conductor, and shows that the processes of electrolytic and metallic conduction are essentially different.

184*. Theory of electrolysis. The theory now commonly accepted as to the condition of a large class of compounds dissolved in water, or any similar solvent, is somewhat as follows. For clearness we will take common salt, or sodium chloride, as the substance and water as the solvent.

Sodium chloride is composed of the two elements sodium and chlorine; the solid compound is assumed to consist of an immense number of separate parts called molecules, each exactly alike and containing each one atom of sodium and one of chlorine. When the

† It varies, according to the electrolyte, from 0.5 to 2 per cent. per 1° C.

solid is dissolved in water it is supposed that these molecules break up, or are 'dissociated,' and that the separate atoms of sodium and chlorine wander about throughout the water; if the solution is not fairly dilute only a small fraction of the whole number dissociate, but if it is very dilute practically all do so.

A difficulty here presents itself, for sodium is a silvery metal which attacks water, and chlorine a greenish strong-smelling gas, and we know that a solution of salt in water does not suggest the presence of either of these. The explanation is that these properties are possessed by the materials in bulk as aggregations of molecules each containing two or more atoms, and there is no reason to suppose that separate atoms, especially when highly charged with electricity, would have the same physical properties.

These wandering atoms are the *ions* when the solution is electrolysed.

The effect of an E.M.F. on such a solution is explained by assuming the presence on each of the atoms of a charge of electricity, $-^{ve}$ on the chlorine atom and $+^{ve}$ on the sodium *.

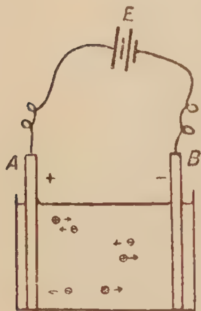


Fig. 112.

These charges must be equal since they neutralize one another when two atoms combine to form a molecule of sodium chloride.

In Fig. 112, which represents a cell containing dilute salt solution with two platinum electrodes *A* and *B*, *A* being the anode, the circles with a + represent sodium ions, those with a − the chlorine ions. If *A* has a charge of + and *B* of − electricity, produced by the battery *E*, the former ion will be urged to the right, the latter to the left. On reaching the electrodes these ions are supposed to give up their charges, and then, since they no longer repel one another, having lost their charges of like electricity, *similar* atoms can combine to form molecules of chlorine and sodium respectively.

Thus + electricity is carried from left to right in the liquid, and − from right to left, constituting a 'current' from *A* to *B*. Thus an electric current passes by *convection* through an electrolyte; and the theory accounts for the production of chemically equivalent quantities

* Part III must be consulted for information as to charges of electricity and their attractions and repulsions.

of all ions by the passage of a definite quantity of electricity, since all ions must carry equal charges.

185*. The theory applies equally well to compound ions, such as SO_4 (sulphion), which carries the – charge in the electrolysis of sulphuric acid, but it must be noted that this is a 'divalent radicle,' and so carries a double charge since it unites with and neutralizes two hydrogen ions. The same is true of the copper ion in dilute copper sulphate; and, generally, the valency of an ion determines the number of times its charge is greater than that of the simple hydrogen ion.

186*. Theory of the simple cell. Consider two plates, of zinc and copper, immersed in a solution of sulphuric acid in water. It is supposed that when any metal is in contact with an electrolyte it has a 'solution-pressure' (analogous to the vapour pressure of a liquid), in consequence of which particles of the metal tend to go into the solvent as ions. Each ion of course bears away its electrical charge, and so leaves the 'parent metal' charged with electricity of the opposite sign; since the charge on the ion of any metal is +, the metal which furnishes these ions will acquire a – charge.

Now, although the charges on all (monovalent) ions are equal, different metals have different 'solution-pressures' in any electrolyte, e.g. in dilute sulphuric acid that of zinc is greater than that of copper, and still greater than that of carbon, or platinum. It is impossible for both metals to send out these ions at once, since in that case the liquid would acquire a constantly increasing charge; the stronger alone will do so, so that in the simple cell it will be the zinc which will part with some of itself and acquire a – charge. As these $+^{ve}$ ions of zinc enter the solvent, ions of hydrogen are driven to the copper plate where they give up their + charge to the copper, and combine in pairs to form molecules of free hydrogen; the + electricity flows round the wire, or other external circuit, to meet the – charge from the zinc, causing an electric current.

The greater E.M.F. of the zinc-carbon couple is explained by the difference of solution-pressures being greater than in the case of zinc-copper.

We have made no mention of the formation of zinc sulphate, as shown in Experiment 28, because that only occurs when the spent acid is evaporated to dryness; so long as 'zinc sulphate' is dissolved in water it is assumed to be separated into ions of zinc and sulphion.

The order in which the commoner metals are arranged when we

consider them from the point of view of solution-pressure is as follows:—

Alkali metals (sodium, &c.).
Zinc.
Iron.
Lead.
Hydrogen †.
Copper.
Mercury.
Silver.
Platinum.
Carbon.

187*. Theory of the Daniell cell. Let Fig. 113 represent plates of zinc (Z) and copper (C) respectively, in aqueous solutions of sulphuric acid (S) and copper sulphate (C'), separated by a porous partition (P).

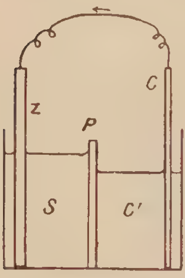


Fig. 113.

As in Article 186, the zinc will pass into the solvent leaving Z with a − charge; the zinc ions will drive the hydrogen ions through P, and these will drive copper ions on to the copper plate C, carrying their free + charges, which will flow through the external circuit as a current of electricity to neutralize the − electricity on the zinc.

After the cell has been in use for some time, there will be round the zinc plate a solution containing ions, which on combination will give zinc sulphate, and round the copper plate ions which will give sulphuric acid.

The student should be able to explain for himself other cases of electro-chemical depolarization.

188*. It will be noticed that ions of hydrogen and of the metals carry a + charge, and those of the non-metals a − charge; hence the non-metals are called electro-negative, the metals electro-positive; and zinc is more electro-positive than copper. Care must be taken not to confuse this statement with the fact that copper is called the positive and zinc the negative *pole of the cell*; the latter names being given because electrically we are more interested in the current in the

† Note the position of hydrogen; it will be referred to again in Article 191.

external circuit, but chemically it is the convection current in the solution that is of importance.

189*. The electron. The theory set out in the last five Articles does not necessarily assume the existence of electrons (see p. 186), but can easily be stated in terms of them; in one or two points it becomes clearer if we do so. We must assume that when a molecule of sodium chloride is dissociated, as in Art. 184, the chlorine ion carries off one electron in excess of its proper share, and is therefore negatively charged, leaving the sodium ion short of one electron, and therefore positively charged. If the ions are divalent, as in Art. 185, they will have two electrons in excess or defect. These excess electrons pass into the anode when the anions give up their charges there, and pass round the circuit to the cathode, where they rejoin the cations; so the current flows round the whole circuit, solid and liquid alike.

190. The following table shows the electro-chemical equivalents of various elements; the second column giving the number of grammes liberated by the passage of 1 ampere for 1 second. The chemical equivalent is given in the third column; from it the atomic weight of the element is found by multiplying by the 'valency' of the element. It will be observed that the chemical and electro-chemical equivalent are in a constant ratio, which justifies Faraday's second law of electrolysis (p. 164).

ELECTRO-CHEMICAL AND CHEMICAL EQUIVALENTS.

Element.	Electro-chemical Equivalent (grms. per coulomb †).	Chemical Equivalent.
Silver (the standard) .	·001118	107·7
Hydrogen . . .	·00001038	1
Potassium . . .	·0004051	39·03
Sodium . . .	·0002387	23
Copper (cupric) .	·0003279	31·59
,, (cuprous) .	·0006558	63·18
Zinc	·0003367	32·44
Lead	·001071	103·2
Nickel . . .	·0003042	29·3
Oxygen . . .	·00008283	7·98
Chlorine . . .	·0003671	35·37

† A 'coulomb' is the quantity of electricity conveyed by a current of 1 ampere in 1 second.

191*. Polarization in the simple cell. The theory of the simple cell, put forward in Article 186, will account for the decrease in its efficiency, which is greater than can be explained by the increase of resistance caused by the hydrogen present on the copper (p. 54). This film of hydrogen has a greater solution-pressure (see Article 186) than the copper, but not so strong as the zinc; hence the E.M.F. of the cell is less when polarized, though it still exists.

192. Back E.M.F. of polarization. If a Daniell cell is connected in series with a delicate galvanometer and an electrolytic cell containing acidulated water and platinum electrodes, on first completing the circuit a small current flows but very soon ceases. If two or more Daniells in series are used, the current continues to flow; it is found that an E.M.F. of 1·47 volts is the least that will serve for the continuous decomposition of water.

In the case, however, of a solution of copper sulphate with copper electrodes, any E.M.F., however small, will produce a continuous current.

If the electrolysis in the former case is stopped, and the electrolytic cell is immediately connected to a voltmeter or high-resistance galvanometer, it acts as an ordinary primary battery having an E.M.F. beginning with 1·47 volts, which very rapidly decreases; in the case of the copper voltameter no such E.M.F. is shown. This must be due to the film of oxygen and hydrogen, on the anode and cathode respectively, acting like the copper and zinc of a simple cell; when these have re-combined to form water the E.M.F. naturally disappears. No such dissimilarity occurs between the two copper electrodes during the electrolysis of copper sulphate.

193. Storage cells, or accumulators. The electrolysis of water into oxygen and hydrogen is an instance of the conversion of electrical energy into the energy of chemical separation. This energy can be changed into the form of heat by mixing and exploding the two gases, or part of it can be changed back into electrical energy, as described in the last article. The fraction of the total amount so re-converted is, however, very small, since all the gas which actually appears as bubbles is lost; some of this can be recovered, as in *Grove's gas battery*, by making the platinum electrodes (of Fig. 111) long enough to reach up into the space occupied by the evolved gases. These electrodes then 'occlude' the gases and act as polarized electrodes,

and of course, as the oxygen and hydrogen are used up, fresh supplies can be provided, so that the contrivance is a true gas battery. Under the best conditions, however, it only gives an E.M.F. of 0·97 volt instead of 1·47, and so is very inefficient, much energy being lost as heat during the absorption of the gases by the platinum.

194. A much more satisfactory method of storing energy by the electrolysis of dilute sulphuric acid into oxygen and hydrogen, which should be able to re-combine and furnish electric energy, was invented in 1860 by Planté, who used lead instead of platinum electrodes. It will be found that these retain their polarization for a much longer time than platinum, if substituted for them in the experiment of Article 192. If these terminals are examined before being discharged, the anode will be seen to be brown, being covered with lead peroxide, while the cathode is grey lead. Planté found that the time of discharge can be increased by running a current through the cell first in one direction, then in another, for a longer time after each reversal, especially if a period of rest is allowed between each. This process he called 'forming' the cell; by it the plates become porous, and after charging, the anode has a deeper surface-layer of lead peroxide, and the cathode a layer of spongy lead readily oxidizable.

When the cell is allowed to furnish a current, the plate which was the anode acts as the + pole, and the E.M.F. is 2·0 volts. When the cell is run down, *both* plates are covered with lead sulphate.

195. Faure discovered, about 1881, that the tedious and expensive process of 'formation' can be greatly shortened by covering the plates with a paste made of red lead and concentrated sulphuric acid; modern accumulators have their plates made of a kind of 'grid' of lead, into the holes of which the paste is pressed, minium (Pb_3O_4) and acid being used for the positive, and litharge (PbO) and acid for the negative plate. The only 'formation' then needed is the passage of a current in one direction for about twenty-four hours, which must be begun directly the plates are immersed in the acid. After this the cells can be discharged, and recharged as often as necessary, the same plates lasting for three or four years.

196. The chemical actions in the cell are very complicated, and imperfectly understood, but, roughly, the conditions when charged and discharged are as follows:—

When fully charged the + plate contains lead peroxide (PbO_2), in contact with strong acid, which latter is also in contact with the − plate containing reduced lead, Pb, in a spongy state.

When discharged as far as possible, both plates are similar and contain lead sulphate ($PbSO_4$) in contact with acid more dilute than before.

The whole of the lead peroxide on the positive plate is not converted into lead sulphate, usually about 50 per cent. remaining unchanged, owing to the inactive layer of lead sulphate on the pellets, which prevents the action of the acid on the active material in the middle of the pellets. Since the 'grid' takes no part in the reaction, comparatively little of the lead present in a cell is directly useful. The ordinary production of lead sulphate during the discharge must not be confused with what is called 'sulphating,' i. e. the production of a layer of a *white* substance on the surface, which occurs when a cell is allowed to stand fully discharged for some time. This is probably Pb_2SO_5, it is non-conducting and causes the plates to buckle. Its formation can to some extent be prevented by the addition of a little sodium sulphate to the acid; but it seldom forms if the cells are kept fully charged or are frequently fully recharged.

197*. During discharge we may consider that oxygen leaves the + plate in the form of ions, which unite with the hydrogen ions in the electrolyte, producing water, and the (SO_4) ions in the electrolyte combine with the lead on both plates. Charges of electricity move with these ions as previously explained, and so cause an electric current †.

We may represent the chemical action between the molecules during discharge thus:—

Charged. $PbO_2 + n \,.\, H_2SO_4 + Pb$

$$\leftrightarrows PbSO_4 + (n-2)\, H_2SO_4 + 2\, H_2O + PbSO_4 \textit{ discharged.}$$

It will be seen that the acid becomes less concentrated the further the discharge proceeds, so that the amount of charge still in the cell may be estimated from the density of the acid, as determined by a hydrometer.

The density of the acid in a fully charged cell is about 1·22, and discharged 1·15, grms. per c.c.

† Since the SO_4 ion carries a negative charge, and during the discharge these ions move towards both plates, it may seem at first sight that no current passes through the acid. It must, however, be remembered that for each SO_4 ion going to the + plate, two oxygen ions leave it, so that an excess of one negative charge leaves the + plate for each negative charge that reaches the − plate on a SO_4 ion. This passage of negative charges from + to − plates is equivalent to a 'current' from − to + plates through the liquid.

198. Electro-plating. The method of depositing a thin coating of copper on the surface of a conductor was shown in Experiment 49; in the same way a coating of silver, gold, &c., can be deposited on objects made of a 'base' metal such as German silver. Silver-plating and gilding are usually carried out in order to make the objects appear more valuable; while articles of iron and steel are generally covered with nickel to avoid rusting. All that is necessary is to make the object the cathode in the electrolysis of a suitable liquid, a solution of the double cyanide of potassium and silver, or potassium and gold, being used. A sheet of the metal to be deposited is used as the anode, to keep up the concentration of the bath. In the case of nickel, the double sulphate of ammonia and nickel is used; a thin coating of copper is first deposited on the iron by the electrolysis of alkaline copper sulphate.

The most important point to attend to is the absolute cleanliness, mechanical and chemical, of the metal on which the deposit is to be made, in order to secure molecular contact with the deposit. The least film of grease or oxide destroys the permanence of the plating.

199. Electro-typing. Exact copies of coins, &c., are made by taking a mould of the coin in plaster of paris, wax, gutta-percha, or 'fusible metal' (an alloy with a low melting-point, e.g. Rose's, which is an alloy of bismuth, tin, lead, and cadmium melting at about 70° C.). This mould has its surface covered with black lead to render it a conductor, or, in the case of fusible metal, is slightly greased to prevent adhesion of the deposit. The mould is then made the cathode in the electrolysis of copper sulphate, and a current passed for some time at a slow rate to ensure a good deposit (see p. 72*d*). The deposited copper will come away from the mould an exact facsimile of the article, and may be gilt or silver-plated if required; it is strengthened by being backed with some easily fusible metal.

The process is largely used for copying the wood-blocks used for illustrating books, whereby any number of prints may be made from copper facsimiles without wearing out the original block.

CHAPTER XV

Thermal Effects

200. If a current passes through a conductor, heat is generated. The amount of heat is usually not sufficient to raise appreciably the temperature of a wire, but passes off into the air; if, however, the current is considerable, or if the wire through which it is forced offers a large resistance, the wire may become red or white hot, or even be melted. This may be shown by putting a battery of low resistance, such as an accumulator, in series with a piece of thin platinum wire (say No. 36). When a long piece, say 15 cms., is in the circuit, the wire will keep cool, since it offers a large resistance and a very small current passes; but as the wire in circuit is shortened the current increases and the wire becomes white hot, and may even melt in spite of the very high melting-point of platinum (1775° C.).

201. The quantity of heat produced per second when a definite current flows through a definite resistance was measured in 1841 by Joule (of Manchester), who wound a wire on a glass tube immersed in a known quantity of water in a calorimeter. A known current was passed through the wire, and from the rate of rise of temperature the amount of heat evolved per second was deduced. The resistance of the immersed wire was measured, and a series of experiments with different currents, resistances, &c., led him to formulate the law which bears his name.

202. Joule's law. *The number of units of heat generated by a current in a conductor is proportional* (1) *to its resistance*, (2) *to the square of the strength of the current*, (3) *to the time during which it flows.*

The law may be expressed in symbols as follows, H being the quantity of heat produced, C the current, R the resistance of the conductor, t the time.

$$H \propto C^2 R t.$$

203. This law may be verified with the apparatus shown in Fig. 114. A calorimeter (A) has a cork (E) carrying a spiral (C) of platinoid wire, and a thermometer (D). In the calorimeter is put

some cold turpentine, or other liquid whose specific heat is low in order that the heat generated may cause a considerable rise of temperature. Some means of stirring the liquid must be provided. A battery (B) of about a couple of storage-cells, an ammeter or tangent galvanometer (G), a variable resistance (R) and a plug-key (P) are connected in series with the wire.

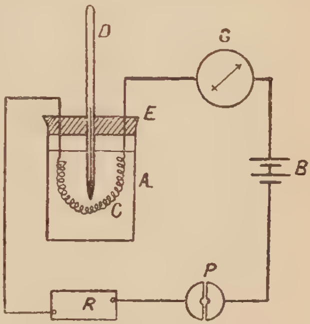


Fig. 114.

Neglecting the loss of heat by radiation, &c., the rise of temperature will be found to proceed at a constant rate if the current is kept steady; if the current is doubled, or trebled, the temperature will be found to rise at four, or nine, times the rate; if another spiral of different resistance is substituted for C and the current is made the same as before, the rate of rise of temperature will be changed in the same proportion as the resistance.

These experiments verify the relation $H \propto C^2 R t$.

204. We may express Joule's law as $H = K C^2 R t$. In order to find the value of the numerical coefficient K, a known mass (M grms.) of water must be substituted for the liquid, and the water equivalent (m grms.) of the calorimeter and coil, and the resistance of the coil (R ohms) must be known *.

The water should be cooled a few degrees below the temperature of the room, and the current C, whose value in amperes must now be known, should be kept running until the temperature is as much above as it was previously below that of the room; this practically eliminates errors due to conduction, convection, and radiation of heat. The rise of temperature ($\theta°$ C.) and the duration of the experiment (t seconds) being observed, we have, since $H = (M+m)\,\theta$,

$$(M+m)\,\theta = K\,C^2 R\,t,$$

from which K can be calculated.

Its value is about 0·24.

$$\therefore \quad H = \cdot 24\, C^2 R\, t.$$

* When the liquid is an insulator, such as turpentine, this wire may be insulated merely with silk, but if more than 1·47 volts are maintained at its ends in water the wire must be insulated with shellac to prevent the passage of the

205*. This constant K is a very important number, as from it the value of J, the 'Mechanical Equivalent of Heat,' can be deduced. Suppose that instead of expressing the current and resistance in amperes and ohms, they are expressed in absolute electro magnetic units (p. 100), being then represented by C_0 and R_0; it can be shown that the value in *ergs* of the work done by the electric current is $C_0^2R_0t$. If each calorie produced is equivalent to J ergs, the value in ergs of the heat produced is JH, and by the Law of Conservation of Energy these two are equal, so that

$$JH = C_0^2R_0t.$$

$$\therefore \quad \frac{1}{J}C_0^2R_0t = KC^2Rt.$$

But 1 ohm $= 10^9$ absolute units of resistance, so that † $R_0 = R \times 10^9$ and 1 ampere $= 10^{-1}$ absolute units of current, so that $C_0^2 = C^2 \times 10^{-2}$.

$$\therefore \quad \frac{1}{J} \times 10^7 = K;$$

$$\therefore \quad J = \frac{1}{K} \times 10^7 = \frac{1}{.24} \times 10^7 = 42000000.$$

Therefore 1 calorie $= 42{,}000{,}000$ ergs.

206. If the current from a few cells is sent through a chain made of alternate links of platinum (P) and silver (S) wires of the same diameter, the platinum wires will glow while the silver wires remain cool, since the specific resistance (p. 125) of platinum is about six times that of silver, and therefore the heat disengaged in the platinum wires is greater than that in the silver.

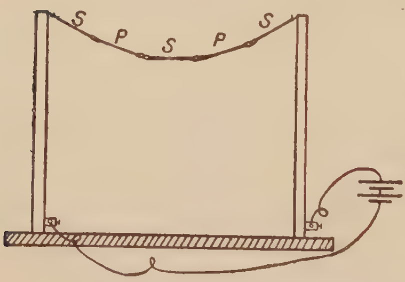


Fig. 115.

207. Again, if a battery is sending a current through a long piece of platinum wire, just insufficient to make the wire red hot, and part of the wire is dipped in a beaker of cold water, the rest of the

current through the water (see p. 170). The coil may be dipped in a solution of shellac in alcohol, and dried in hot air. The coil may be an open one, of No. 28 platinoid wire, with a resistance of from 10 to 20 ohms.

† Remember that R_0 and R represent the same resistance, but R_0 is the numerical value of the resistance expressed in units which are small compared with ohms, so that R_0 is a number which is large compared with R.

wire will become red hot. This is due to the fact that the resistance of a metal is greater when it is hot than cold (p. 129), so that cooling part of the wire reduces the total resistance of the circuit, thus increasing the current and so producing more heat in the uncooled portion of the wire.

208. The thinner the wire of a given material through which a given current passes, the hotter that wire gets, because its resistance is greater and the surface by which it can lose heat to the air is smaller. Advantage is taken of this in practice, in the provision of a 'fusible cut-out,' consisting of a comparatively thin piece of pure tin wire, inserted in the electric-lighting circuit where it enters the house. If through an accident in the house a dangerously large current is allowed to flow along the wires, this tin wire, having a low melting-point, melts and breaks the circuit. In this way the wires cannot grow hot at any place where they might set fire to woodwork.

209. Power spent in maintaining a current. We may write Joule's law as stated in Art. 204 in the form

$$C^2Rt = \frac{1}{\cdot 24} H = 4{\cdot}2 \times H.$$

By Ohm's law $E = CR$, E being the P.D. in volts between the ends of the conductor of resistance R ohms, which is driving through it the current C amperes.

So Joule's law becomes $C \times E\,t = 4{\cdot}2 \times H$.

Now the right-hand side of this equality represents, since heat is a form of energy, the energy which is produced by the current; therefore by the Law of Conservation of Energy it must represent the energy transmitted from the dynamo or battery which produces the current. We can therefore measure the energy expended per second in producing a current by the product of the P.D. (in volts) by the current (in amperes) which it produces. This 'energy expended per second' is a rate of doing work, or *power*, and the name given to the unit of electrical power is a **Watt**, defined as the *power of one ampere driven by a P.D. of one volt.*

To find then the power supplied by a dynamo or battery, the number of amperes of current supplied must be multiplied by the P.D. in volts at which it is supplied. The result will be expressed in watts.

Since 1 volt = 10^8 C.G.S. units of E.M.F. (p. 104) and 1 ampere = 10^{-1} C.G.S. unit of current, 1 watt = $10^8 \times 10^{-1}$ or 10^7 C.G.S. units of power, i.e. 10^7 ergs per second.

Now the power of a machine is usually expressed in terms of a 'horse-power,' which equals 746×10^7 ergs per second, as is shown in text-books on dynamics.

Therefore 1 horse-power = 746 watts.

210. The glow-lamp is the most usual application of electricity to lighting. The lamp contains a filament of carbon or tungsten which is made white hot by a current. Since white hot carbon burns in air, the filament (*A*, Fig. 116) is enclosed in a glass bulb *B*, from which very nearly all the air was extracted before the bulb was hermetically sealed at the point *C*. The current is carried through the glass by wires (*D*) of platinum. This is the only metal having the same 'coefficient of expansion' as glass, and hence capable of filling exactly the hole through the glass while they heat and cool together. These wires pass through plaster in a brass cap *E* by which the lamp is fitted in its holder; the ends of the wires are connected to two contact pieces on the end of *E*, by which connection is made to two spring studs in the holder, which are connected to the 'mains.'

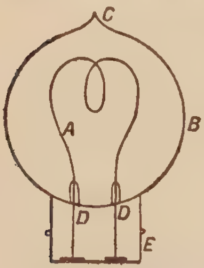


Fig. 116. Glow Lamp.

These lamps are arranged 'in parallel,' so that any one may be cut out at pleasure without affecting the others; a constant E.M.F. is maintained by the dynamo (*A*) in the supply station, whatever the number of lamps taking current from the mains (*B*).

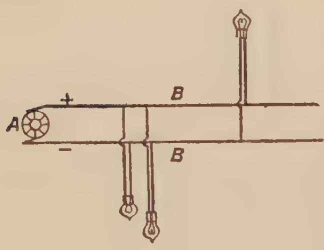


Fig. 117.

211. The current taken by a lamp depends on its candle-power and the E.M.F. of the supply; a carbon lamp needs about 4 watts per candle-power, so that, for example, a 16-c.p. lamp would need 16×4 or 64 watts, which would be produced by ·64 ampere at 100 volts, or ·32 amp. at 200 volts, or ·29 amp. at 220 volts, or 8 amps. at 8 volts, since the watts consumed are measured by the product of the P.D. in volts by the current in amperes (see Art. 209). The 'efficiency' of a lamp (i. e. the number of c.p. it gives per watt) varies with different makes, and is made higher for lamps intended to be

run off small batteries of accumulators or dry cells; lamps with lower efficiency have the longer life, burning about 1000 hours, although it is generally profitable to replace them sooner than this. The efficiency of metal filament lamps is about 1 watt per candle-power.

212. The arc-light. If a piece of carbon is connected to each of the wires from a battery or dynamo which maintains an E.M.F. of at least 40 volts, and if these pieces are made to touch and are then drawn apart about half a centimetre, a very bright light is produced. As they are drawn asunder the extra current at break (p. 155) volatilizes some carbon, and the vapour serves as a conductor, so that the current is maintained across the gap.

The end of the carbon connected to the positive pole is intensely hot, probably at the highest temperature that we can produce; the negative carbon is red hot, probably because it is so near the other carbon. Between the two is a kind of 'flame' of a blue-violet colour. It is supposed that, starting from the + carbon, we have, first a thin layer of carbon vapour, then a 'mist' of carbon, the whole surrounded by a thin sheath of carbon vapour burning in air.

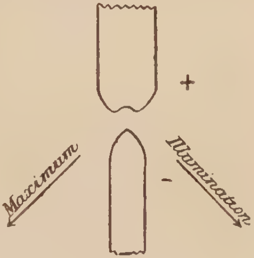


Fig. 118.

As the current flows, the positive disappears twice as rapidly as the negative carbon, hence the former is generally made thicker than the latter. Some carbon distils over from the positive to the negative; the negative assumes a pointed form, and a crater is formed in the end of the positive carbon, from which crater the light chiefly comes. It is almost impossible to determine the temperature of the crater; it is probably about 3,500° C.

213. If carbon at this temperature were exposed to air it would burn away very rapidly, but in this case it is protected to some extent by the products of combustion. In lamps of the 'enclosed' type, the carbons are contained in a small glass globe which is almost air-tight, so that the rate of consumption of the carbons is very small. In all cases, however, the lamp must be provided with an electrically-controlled mechanism for keeping the carbons in contact when no current is flowing, and for separating them to a suitable distance as soon as the current begins to flow. As the carbons consume away the arc lengthens until it breaks; the carbons then again come into

contact and are separated by the mechanism. Thus an arc-lamp periodically goes out for a moment.

214. When the current is flowing steadily, the arc seems to exert a 'back E.M.F.' of about 39 volts, probably due to the absorption of energy on the surface of the positive carbon in the process of volatilizing the carbon. The resistance of the arc itself is not more than about half an ohm, so that it is necessary to insert a suitable resistance in series with it; for example, on a 100-volt circuit, 6 ohms in series with the arc would allow about 10 amps. to pass, which would give a light of about 2,000 c.p. For search-lights, &c., currents of 100 amps. or more are used. Arc-lamps are commonly run in groups of two or three in series; for example, if the 'pressure' of the mains is 220 volts, groups of five in series would be used.

Since the light comes chiefly from the crater, the amount radiated differs with the direction, the maximum being at an angle of about 45° with the line of carbons. Hence the efficiency cannot be stated so definitely as in the case of glow-lamps, but it may be taken as in practice about $\frac{3}{4}$ watt per c.p.

215. Thermo-electric effects. In 1821, Seebeck of Berlin discovered that if a circuit is composed of two different metals, and if one of the junctions of these metals is kept at a higher or lower temperature than the other, an electric current flows round the circuit.

For example, if *A B C* represents an iron wire, soldered or brazed at its ends to copper wires which are connected to the copper wires of a galvanometer *G*, and if *A* is heated to a higher temperature than *C*, then the galvanometer will show a current in the direction *A B C G*. The galvanometer must be a sensitive one, as the E.M.F. is very small; for example, if *A* is kept at 100° C. and *C* at 0° C. the E.M.F. round the circuit will be only ·0013 volt.

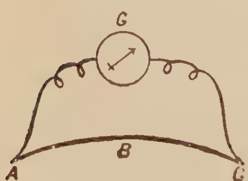


Fig. 119.

The effect will be much larger if the point heated be the junction of bismuth and antimony, instead of copper and iron; these are the best of the commoner metals for the purpose *. The metals may be

* Selenium or tellurium give a much greater E.M.F. than antimony.

in the form of bars *A B*, *B C* (Fig. 120), united at their ends to form a V, with their other ends connected to a galvanometer *G*. Of course this is now not a circuit of two metals only, but the introduction of the third metal, copper, does not make any difference, if the junctions at *A* and *C* are both at the same temperature. This follows from the experimental fact that the E.M.F. gained in passing from bismuth to copper, together with that gained in passing from copper to antimony, is the same as the E.M.F. gained in passing direct from bismuth to antimony, the three junctions being at the same temperature.

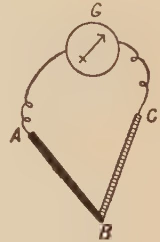


Fig. 120.

The current flows from bismuth to antimony across the hot junction, and if *A* and *C* are kept at 0° C. and *B* at 100°, the E.M.F. round the circuit is about ·014 volt.

Such an arrangement is called a *thermo-couple*.

216. The thermopile. The effect is increased by using a large number of thermo-couples in series, as in Fig. 121 (where the black bars represent bismuth and the unshaded ones antimony), and heating alternate junctions, *A*, *C*, *E*, &c., while *B*, *D*, *F*, &c. are kept cool. In this way the E.M.F.'s at the hot junction from bismuth to antimony are all in one direction round the circuit and so add their effects, like cells in series. Adjacent rods are usually insulated from one another, except at the ends, by slips of mica. Fifty-six or more of such pairs of rods are piled together so that the ends *A*, *C*, &c. form a square, and are mounted in cork in a brass stand, the whole being called a Thermopile. When the terminals are connected to a sensitive galvanometer of low resistance, on warming one of the square faces a current will be shown by the galvanometer. This constitutes an exceedingly delicate thermometer, very well adapted for the detection of radiant heat.

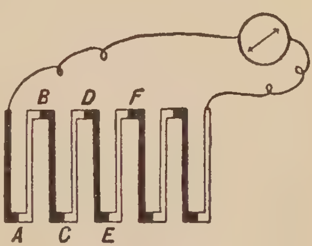


Fig. 121.

In Fig. 122 the pile of rods of bismuth and antimony is represented

by A B, C is the cork inside the brass case D, E a cap to keep the joints at the ends (A) of the rods at a uniform temperature, F a cone of polished metal to concentrate the radiant heat on the face B. On the base of the stand are two binding screws connected to the ends of the last of the series of rods.

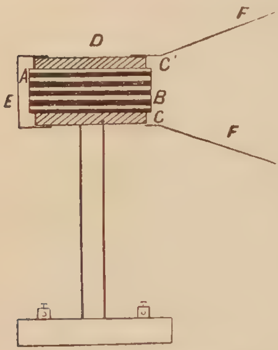


Fig. 122. Thermopile.

217. Reversible effect at a junction. When the junction of two metals forming part of a circuit is heated, a current of electricity is produced, and by the law of conservation of energy the heat supplied must disappear, since the energy of the electric current is produced at the expense of an exactly equal quantity of energy in some other form. The existence of this absorption of heat by the passage of a current of electricity from one metal to another was proved experimentally by Peltier in 1834; it is usually called the 'Peltier effect,' and is the converse of that discovered by Seebeck.

Peltier found that if a current of electricity is sent by a battery through such a conductor as A B C in Fig. 123, where A and C are bars of antimony and B a bar of bismuth, then at the junction of A and B heat is generated, and at the junction of B and C it is absorbed, by the passage of a current in the direction of the arrow. If, however, the current is reversed, the junction B C will be heated, and A B will be cooled.

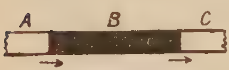


Fig. 123.

218. This Peltier effect is altogether separate, and different in kind, from the ordinary 'Joule effect' (p. 174), and the two occur together in a compound circuit such as A B C. The differences are (1) the Peltier effect occurs at a junction, the Joule effect throughout the whole conductor; (2) the amount of heat evolved or absorbed in the Peltier effect is proportional to the current, in the Joule effect to the square of the current; (3) the Peltier effect is reversible with the direction of the current, the Joule effect involves an evolution of heat whichever way the current runs.

219. The existence of the Peltier effect may easily be shown as follows:—

Connect a thermopile (*A*, Fig. 124) to a three-way key *K L M*, by which it may be put in series either with a galvanometer *G*, or a Leclanché cell *B*.

The caps should be kept on both ends of the thermopile, and *K* should be connected with *M* as a preliminary experiment to test whether both its faces are at the same temperature (shown by the absence of deflection in *G*). Now connect *K* with *L* for about ten seconds, then disconnect *K* from *L* and connect it to *M*. A current will flow, showing that the faces are at a different temperature. This cannot be due to the heat evolved in *A* by the Joule effect since that would affect the faces equally; also if the experiment is repeated with the poles of *B* reversed the consequent current in *G* will be reversed. The longer the current runs through *A*, the greater will be the current afterwards produced in *G* by *A*.

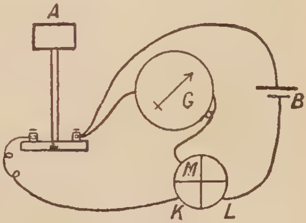


Fig. 124.

Thus the thermopile forms a kind of storage cell; many attempts have been made to use it as a primary battery on a commercial scale to furnish electric current direct from heat, but they have failed because the E.M.F. falls off with use. This is owing probably to changes of the metals at the hot junction. The loss of heat by conduction towards the cold junction also prevents efficiency.

CHAPTER XVI

Passage of Electricity through Gases; Wireless Telegraphy

220. Gases, such as air, at atmospheric pressure and under ordinary conditions, are good insulators unless the P.D. is very large. For instance, if we have two small metal spheres separated by an air gap of 1 cm. and gradually raise the P.D. between them, no appreciable current passes through the air until we reach about 20,000 or 30,000 volts, when the conditions suddenly change; a spark passes between the spheres and the resistance of the air gap falls momentarily to a comparatively few ohms. But if the air in the gap is 'ionized' by passing X rays through it, or by bringing a little radium near it or by other means, a much lower P.D. causes a small but steady current to flow; the magnitude of this current does not increase with the P.D. It is therefore clear that gases differ from metals as regards the conduction of electricity.

We are not greatly interested in these complications in the conductivity of gases at ordinary pressures; but the researches prosecuted during the past 25 years into the passage of electricity through gases at very low pressures have been immensely fruitful in results of practical commercial value and of vivid theoretical interest. These researches have thrown a flood of new light on the constitution of matter and on its relation to electricity, and the discovery of new secrets proceeds apace. For the sake of brevity and simplicity it will be convenient to disregard here the historical order of discovery, and give an outline of some of the phenomena, with the knowledge to which they have led us.

221. Cathode Rays. The simplest apparatus for observing the behaviour of a rarefied gas when an electric discharge passes through it is shown in Fig. 125 *a*. It consists of a glass tube, which originally contained air or some other gas, nearly all of which has been pumped out; the vacuum should be higher than in an ordinary electric light bulb, the pressure being about $\frac{1}{300}$ mm. of mercury, say $\frac{1}{200000}$th of atmospheric pressure. Metal electrodes *A* and *C* are supported by

platinum wires sealed into the glass; the terminals of an induction coil, capable of producing a spark in air about six inches long, are connected to these electrodes so that *A* is the anode and *C* the cathode.

When the coil is in action, a velvety coating of light covers the cathode, and faint bluish streams of light can be seen to proceed in straight lines from the cathode, starting out at right angles to its surface; these are called Cathode Rays. These rays excite a flickering greenish phosphorescence where they strike the glass walls of the tube. If a solid body, such as *A*, is interposed in their path, it casts a shadow on the walls of the tube; to this extent they resemble rays of light. But in some respects they behave very differently. For instance, the rays can be bent by creating a magnetic or electric field of force at right angles to them; rays of light are not affected in this

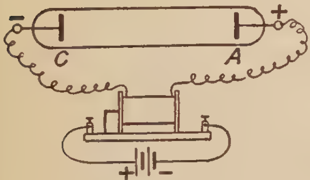


Fig. 125 *a*.

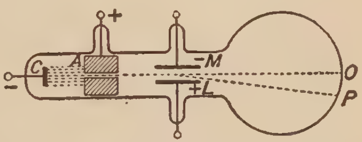


Fig. 125 *b*.

way. The only explanation which fits all the observations is that they consist of charged particles (called electrons) moving at very high speeds. The form of tube used by Sir J. J. Thomson for showing this and other phenomena of cathode rays is shown in Fig. 125*b*.

The anode *A* is pierced with a very fine tube to isolate a narrow pencil of cathode rays; this pencil passes between two parallel plates, *L* and *M*, which are connected to the poles of a storage battery so that an electric field of force is created between them. The spot of fluorescent light, marking the point where the pencil of cathode rays strikes the glass, is seen to shift from *O* to *P*, to a greater or less extent according as the P.D. between *L* and *M* is increased or diminished. As the ray is bent towards the $+^{ve}$ plate the particles must carry a $-^{ve}$ charge (see Art. 237).

If instead of the electric field we create a magnetic field, at right angles to the plane of the paper in Fig. 125*b*, by means of magnet poles outside the tube, the ray will be bent in a similar way. A flight of charged particles is of course exactly like an electric current, and

so a magnetic field should affect it (see p. 143); in fact it is easier to think of a current being caused by electrons flying freely through space than by the same electrons passing through the entanglements of molecules in a wire as described on p. 46.

If the amount of bending of the cathode rays is measured in each of the above cases for known strengths of the electric and magnetic fields, we can calculate both the speed of the particles and also the ratio of the mass of each particle (m) to the quantity of electricity (e) on it.

The speed of the electrons in the cathode rays is thus found to vary from about one-tenth up to about one-third of the speed of light (roughly 100,000,000 miles an hour) depending mainly on the P.D. between the anode and cathode of the tube. The ratio m/e is found to be constant, whatever be the pressure or nature of the gas in the tube, the material of the electrodes, the P.D. between them, &c.; this supports the view that we are here dealing with particles common to all substances. The value of m/e is about $5{\cdot}65 \times 10^{-9}$ grm. per coulomb. We have considered the ratio m/e in another case, that of electrolysis (see Chap. XIV); its value for the hydrogen ion in solution is about $1{\cdot}04 \times 10^{-5}$ grm. per coulomb (see p. 169). So m/e for the hydrogen atom is about 1,840 times as large as m/e for the electron; hence either the mass of the hydrogen atom is much greater than that of the electron, or it contains much less electricity, or both may be true. Which of these is the case can only be decided by an independent experiment; a different way of measuring the quantity of electricity in an electron (which would occupy too much space to explain here) shows that it is the same as that in a hydrogen ion in solution; so we are driven to the conclusion that the mass of an electron is about $\frac{1}{1800}$th of that of the hydrogen atom, which was previously believed to be the lightest thing in existence.

222. Free electrons. It is not only by producing cathode rays in a discharge tube that we can get free electrons; for example, radioactive materials such as radium emit them when cold, and metals (e.g. the filament of an electric glow lamp) do so when white hot. This latter effect is used in Thermionic valves, which will be described later (p. 191*d*); the cause of it is probably as follows: When a solid is heated, there is an increase in the number of electrons migrating from atom to atom (see p. 46), and in the speed at which they travel between atoms; the heat-energy put into the solid takes the form of

kinetic energy of the electrons. Incidentally we may remark that if one part of the solid is heated the electrons in that part travel away into the surrounding parts, carrying their kinetic energy with them; this accounts for the conduction of heat in a solid. It also explains why metals (in which electrons freely break out of atoms and move about between them) are better conductors of heat, as well as of electricity, than such substances as glass and other insulators (see p. 202), in which the electrons are much more constrained. As the electrons in a hot body move indiscriminately in all directions there is no flow of electricity in one direction more than another; it is only when an electric force urges them all in one direction (see p. 46) that an electric current is produced.

The electrons will not ordinarily break out through the surface of a solid; the attraction of the positive nuclei in the solid restrains them; but if the temperature is very high indeed, as it may be in the tungsten filament of a glow lamp (which has a melting-point of 3,270° C.), the electrons move fast enough to overcome this attraction, and travel off freely into the space surrounding the wire. The rate of emission may be great enough to produce an outflow of electricity from the white-hot surface at the rate of one ampere per sq. cm.

223. X Rays. When the electrons in the cathode rays strike any solid body, such as the glass walls of the tube, or the anode if that lies in their path, they give rise to another sort of radiation, called X rays (or Röntgen rays, after their discoverer). These rays spread out in all directions from the surface of the body where it has been struck by the cathode rays, and proceed in straight lines; they pass through transparent bodies, such as glass, and hence emerge from the tube into the air. They are now known to be light of much smaller wave-length than ordinary visible light. Their wave-length is so short that they will penetrate many solid bodies which are opaque to ordinary light, such as human flesh, cardboard, wood, &c.; but denser bodies such as bones, metal, &c., are less transparent to them. They affect a photographic plate in the same way as ordinary light. Hence, if we give a suitable length of exposure we can photograph the bones, or shell fragments, contained within flesh, or air-holes in metal castings; the practical uses to which X rays are put are very numerous, and too well known to need description here.

The wave-length of the X rays depends on the material of the solid body in the discharge tube, which emits them when struck by

the cathode rays. Each element emits its own characteristic wave-lengths of X rays, just as it emits its own characteristic wave-lengths of visible light. The usual process for measuring the latter is to pass sparks between electrodes (in air) of the solid element to be investigated, or to pass an electric discharge through the gas (at a moderately low pressure) and by means of a 'diffraction grating' to obtain a spectrum of the light so produced. This diffraction grating consists of a piece of glass having very fine lines scratched on it, very close together; alternate transparent and opaque bands are thus formed, the breadth of each being not much greater than the wave-length of the light that we want to analyse. Such a grating produces no effect on X rays; but for them a crystal (say, calcite) provides a suitable diffraction grating. In a crystal the atoms are packed together in orderly fashion and they serve as the required opaque bands, since they are found to be at a distance apart suited to the wave-length of X rays. In this way the X rays emitted by a platinum 'anti-cathode' are found to have a wave-length of about one millionth of a millionth of a millimetre. The wave-length of yellow light is about 600 times as large as this.

The wave-length of ordinary light sets a limit to the 'resolving power' of the most perfect microscope that could be constructed; that is, we cannot hope to distinguish particles smaller than a certain size; for example, there is no chance of magnifying a solid body such as a crystal sufficiently to see how the atoms are arranged in it. But the smallness of the wave-length of X rays allows us to discover this; we cannot actually see the atoms in a crystal, but we can measure the distance between them in various directions and can tell how they are grouped.

224. Positive Rays. If the cathode of the discharge tube in Fig. 125*b* is pierced with holes, the glass behind it will be seen to phosphoresce with a faint bluish light. We can use the tube shown in Fig. 125*a* to study the rays which cause this phosphorescence; for this purpose the terminals of the induction coil must be coupled to the tube the other way round, so that C becomes the anode and A the cathode. These rays affect a photographic plate, and the most convenient and accurate way to determine the value of OP is to put such a plate inside the bulb, and develop it in the ordinary way, when an image will be found wherever a ray has struck the plate. It is found that both magnetic and electric fields deflect these rays, but in the

opposite direction to cathode rays, so they most probably consist of particles containing *positive* electricity. They are therefore called Positive Rays.

If for simplicity we imagine that the gas in the tube is absolutely pure argon, and if we apply both magnetic and electric fields simultaneously, in such a way that the lines of force of both fields lie in the same plane instead of at right angles to one another (as they did in the experiment with cathode rays), it will be found that the particles have all struck the photographic plate at points lying along a curve, such as PP' in Fig. 126a; here O is the point where the rays strike the plate when the electric and magnetic fields are not turned on, and OM is parallel to the lines of force of the fields.

Theory shows that if m is the mass of the particle which strikes the

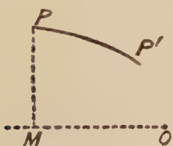


Fig. 126 *a*.

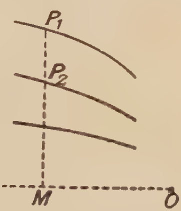


Fig. 126 *b*.

plate at P, e the quantity of electricity on it, and v its velocity, then OM/PM^2 gives the value of the ratio m/e, and PM/OM gives the value of its velocity v. Since PP' is not a straight line through O, the ratio PM/OM is not the same for every point of the curve; so the velocities of the particles differ. The particle striking at P' has the highest speed, and this is found to be far smaller than that of the electrons in the cathode rays. It is found that the curve is of such a shape that OM/PM^2 is the same for every point on it (the curve is a parabola with its vertex at O); so that m/e is the same for all the particles of argon. It is found that the value of m/e is many hundreds of times as great as for an electron; so either the mass of the positive particle of argon is much greater, or the quantity of electricity on it is much less, than in the case of an electron.

As a matter of fact, it is impossible to attain absolute purity of the gas in the tube; traces at any rate of other gases will be present, and each will contribute its quota to the positive ray. But each such substance produces its own separate curve on the plate, as in Fig. 126b,

and the corresponding value of m/e can be deduced from that curve. For the positive particle of hydrogen the value of m/e is found to be the same as for a hydrogen ion in solution (see p. 169); this at least suggests that the positive particle in this case is a hydrogen atom which has lost a single electron. All the evidence points to the conclusion that these positive rays are composed of atoms or molecules * which have lost one or more electrons, and so are 'positively charged.' The loss of one or two electrons is most usual, but mercury atoms can lose any number up to eight.

It is probable that these electrons were torn away from the atom or molecule of the gas in the tube by the intense electric field between the anode and cathode; that the electron then went towards the anode and the positively charged atom towards the cathode, under the influence of this electric field; the nearer the atom was to the anode when it lost its electron, the higher the speed it would attain before reaching the cathode; this would account for the differences in speed observed in the rays after passing the cathode. We get samples of all the particles flying about in the tube between the electrodes; for instance, in an often-quoted experiment on a tube originally filled with nitrogen extracted from the atmosphere, the photographic plate showed curves corresponding to mercury atoms with a single, a double, and a treble charge, nitrogen atoms with a single and a double charge, and the following with single charges: molecules of nitrogen and carbon dioxide, atoms of argon, neon, oxygen, and carbon.

By means of a set of curves such as that in Fig. 126*b* we can at once compare the atomic weights of the substances contained in the tube; for example, to take a simple case where P_1 is the trace of a nitrogen atom (atomic weight m_1) and P_2 that of a carbon atom (atomic weight m_2), each with a single charge e, we have

$$\frac{m_1}{e} : \frac{m_2}{e} = OM/P_1M^2 : OM/P_2M^2,$$

or

$$m_1 : m_2 = P_2M^2 : P_1M^2.$$

One great advantage of this method of obtaining atomic weights is that impurities in the sample do not affect it, since they merely produce other curves; another is that it separates substances with the same chemical properties but different atomic weights.

* A molecule consists of two or more atoms, of the same or different elements, linked together and forming a single particle.

225. Wireless Telegraphy : Production of Waves. Induction coils are used for wireless telegraphy as well as for X ray work; for the former purpose they are provided with a condenser (*C*, Fig. 127*a*), consisting of two or more Leyden jars (p. 250), as a shunt to the spark-gap, *S.G.*; this must not be confused with the condenser used as a shunt to the hammer break in the coil. This extra condenser has a marked effect on the spark; it makes it shorter and 'fatter,' for the following reasons: When the current in the primary of the coil is stopped, the current thereby induced in the secondary is at first devoted to charging up the condenser *C*; it is only when the P.D. between the two plates of *C* has thus been brought up to a sufficient height to cause a spark across *S.G.* that a spark will pass. If the capacity of the condenser is fairly large, this takes most of the very short time during which the high E.M.F. in the secondary lasts, so that the P.D. across the spark gap never rises so high as it would without the condenser *C*. But if the spark gap is reduced * a spark will pass at each stoppage of the primary current. The first part of this spark will be the same as if *C* had been absent, a flow of electricity from, say, the ball *S* to the ball *G* through the air completing the circuit of the secondary of the coil. At the same time the electricity stored in the condenser will discharge itself in the same direction across the spark gap, which accounts for the increased 'fatness' of the spark. Another effect of the condenser *C* now shows itself; when the electricity from the condenser has started surging across the spark gap it goes on flowing after the condenser has been discharged, and charges up the condenser the other way round, until it attains nearly the same P.D. as before. Since the resistance of the spark gap drops to a few ohms directly a spark has passed (see p. 152), the condenser will discharge itself again; so we shall get a series of surges backwards and forwards across the spark gap. This process is very similar to the swinging to and fro of a pendulum, which, when once started, goes on, but with steadily decreasing amplitude of oscillation until all its energy has been expended in overcoming the

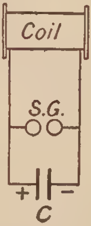


Fig. 127 *a*.

* An ordinary length of gap for a coil used for wireless is about $\frac{1}{10}$th inch, which needs about 10,000 volts to start a spark; without the condenser the coil might be able to spark through 10 inches, requiring about 150,000 volts.

air resistance. In this case the electric energy is expended in $C^2 R$ effect (see p. 177), chiefly in the spark gap, since the resistance of the rest of the circuit is small; the oscillations are therefore 'damped' as in the case of the pendulum, and die away after perhaps 10 or 20 of them have been performed.

It should be noted that the secondary of the coil takes no appreciable share in this surging to and fro after its first discharge; its resistance and self-induction (see p. 154) are so high that the spark gap offers a much better path for the electricity between the plates of the condenser.

The time occupied by each oscillation depends on the capacity of the condenser and on the resistance and self-induction of the rest of the circuit; such an arrangement has a 'natural' or 'free' period of swing, just as a pendulum has. This may in practice be anything from one-ten-millionth to one-thirty-thousandth of a second. Hence, with this arrangement, the function of the induction coil is to start a freely oscillating current through the spark gap and the wires connecting it to the condenser.

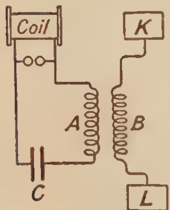


Fig. 127*b*.

Suppose now that one of these wires is made into a coil A, lying within another coil B, as shown in Fig. 99 on p. 150; in Fig. 127*b*, A and B are represented as lying side by side, as is generally done for clearness in these diagrams. Whenever the current in A increases or decreases, an E.M.F. is induced in B, first in one direction, then in the other; if the ends of the coil B are connected to two large metal plates, K and L, electricity will surge backwards and forwards between them as this E.M.F. changes its direction. When this arrangement is used for Wireless, K usually takes the form of an Aerial, or Antenna, consisting of wires supported on high masts, and L is either the earth or one plate of a condenser whose other plate is connected to earth.

This second system, consisting of the aerial, the coil B, and the earth, has its own natural period of oscillation, just as the other circuit has. If these two periods are equal to one another, the changes of current in A will produce the maximum effect in B, since the E.M.F. which they induce in B then comes at the right time and in the right direction to help the swing which was started by earlier impulses from A. This equality of period is produced by adjusting the various

resistances, capacities, &c., of the two circuits; this is called 'tuning' them.

The oscillations in this second system will not die away so rapidly as those in the first, since there is no spark gap to dissipate energy.

226. Wireless Waves. At the moment of the oscillation when K and L are charged up, a complete field of electric force (see p. 208) exists round them, the lines of force reaching between K and L. As K and L discharge themselves by a current through B, this field is destroyed; as the plates are charged up the other way round, the field is recreated with the lines of force in the opposite direction. Thus at every point of space round the aerial the direction and magnitude of the electric force changes with every surging to and fro of the charges on K and L. In the same way when the current flows between K and L it produces a magnetic field consisting of circular lines of magnetic force having their centres in B, and this field is destroyed and reversed with each reversal of the current.

It might of course happen that these fields of force were created exactly simultaneously throughout their whole extent. This however is not the case; it is found to take a finite (though very small) time for the effect to reach a distant point, so that the destruction or creation of the force at that point occurs a little later than the electric change at $K\,L$ which causes it. Hence electric and electromagnetic *waves* spread out from $K\,L$, since points at various distances from $K\,L$ are affected in turn according to their distance from $K\,L$. These waves are found to move with the same speed as light, i. e. 3×10^{10} cm. per sec.

This movement of waves is entirely different from the movement of electricity through gases; no electrons or ions take part in it. In fact, the passage of these waves through the air is actually hindered by the presence of electrons or ions, and it is stopped entirely if they are very numerous. This is one at least of the reasons why wireless waves can travel round the curve of the earth's surface, and so can be detected at points far below the horizon of the transmitting aerial; the upper atmosphere is highly 'ionized,' and therefore reflects the waves downwards instead of allowing them to pass through it into outer space.

For sending wireless messages a tapping key is included in the primary circuit of the coil, and words are spelled out by means of the Morse code (p. 135). If the key is held down for, say, half a

second, 10 or 20 sparks will pass and each will produce a train of a few hundred 'damped' waves, spreading out into space from the aerial, with a frequency usually lying between 10,000,000 and 30,000 a second and so having a wave-length between 30 and 10,000 metres.

227. Receiving Circuit. When it is required for receiving, the aerial is disconnected from the transmitting system, and connected to earth through a coil and condenser. If the natural period of this arrangement is made the same as that of the waves which reach the aerial from the sending station, electric oscillations will be set up by induction in this receiving aerial and coil. We have now to consider how their existence can be detected.

The simplest plan would seem to be to include a telephone receiver (p. 137) in the receiving circuit, but there is one fatal objection to it; the frequency of the oscillations is so high that the telephone would not produce an audible sound. The pitch of the highest note which the human car can detect is about 16,000 vibrations per sec., and the lowest radio-frequency used is about 30,000 per sec.; it is usually far higher. Hence an indirect method must be adopted; many different detectors have been designed, but only two, of the type called 'rectifying detectors,' will be explained here; for more complete information on this very large subject text-books on wireless telegraphy must be consulted.

228. Crystal Detector. If certain crystals are placed in contact with one another, or with certain metals, so as to have a very small area of contact, a circuit including them does not obey Ohm's Law; the graph connecting current and P.D. is not a straight line, but a curve. For example, a typical curve for carborundum in contact with steel is given in Fig. 128*a*. The ordinates represent currents and the abscissae represent the P.D. between points in the carborundum and steel near the point of contact. The cause of these peculiarities is not fully understood.

Suppose a current is flowing from carborundum to steel, of magnitude represented by PM, where P is a point on the sharp bend of the curve; if the P.D. (represented by OM) is increased or decreased by equal amounts (MM_1 and MM_2) it is clear from the shape of the curve that the corresponding increase in the current ($P_1M_1 - PM$) is considerably greater than the decrease ($PM - P_2M_2$). Hence if we have a steady P.D. of about 0·7 volt across such a junction, and if we superimpose on it an oscillating P.D. which will cause the combined

P.D. to rise and fall an equal amount above and below its former value, the 'average' P.D. $\frac{1}{2}(OM_1 + OM_2)$ will be unchanged, but the 'average' current $\frac{1}{2}(P_1M_1 + P_2M_2)$ will be increased. This of course would not occur if Ohm's Law held good here.

Fig. 128*b* shows the connections by which this can be effected. C represents the carborundum crystal, S the piece of steel; S is connected through a low-reading ammeter A to some point E of a resistance through which a battery B maintains a steady drop of potential. C is connected to the positive end of this resistance through a coil K. Thus E can be adjusted to give the steady P.D. between C and S represented by the abscissa of the best point, P, on the curve

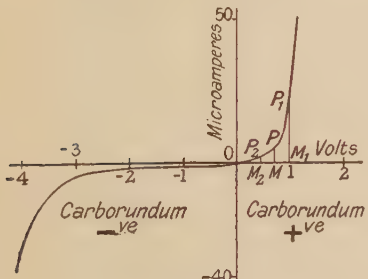


Fig. 128*a*.

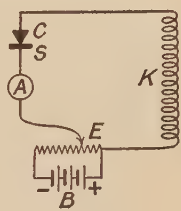


Fig. 128*b*.

of Fig. 128*a*. If an oscillating P.D. is set up by some means in the coil K, this will be superimposed on the steady P.D. produced by B, and an increase will consequently take place in the average current round the circuit; this will be shown by the ammeter.

229. Vacuum oscillation valves. Fig. 128*c* represents another form of rectifying detector, called a Three-electrode thermionic valve; it produces the same results as a crystal detector, though it is based on different principles. It consists of a glow-lamp bulb with a tungsten filament F, which is kept white hot in the usual way, by connecting a battery to its terminals $F'+$ and $F'-$. Surrounding but not touching this filament is a 'grid' G, formed of a close spiral of wire, with a separate lead passing out of the bulb to a terminal G'. Surrounding this grid is a metallic 'plate' P (shown broken in the diagram, to disclose the grid and filament) with its own separate lead and terminal P'. A very high vacuum is created in the bulb.

If we raise the potential of the grid (G in the diagrammatic

Fig. 128*d*) by a few volts, and the potential of the plate P by 50 or more volts, above that of the negative end of the filament F, by

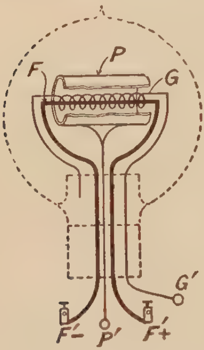


Fig. 128 *c*.

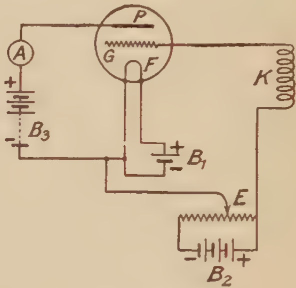


Fig. 128 *d*.

means of the batteries and connections shown in that figure, we shall find that a small but steady current flows into the plate P from outside the bulb. This may be measured by a low-reading ammeter A.

If we vary the potential of the grid by means of the potentiometer arrangement E, the current into the plate will be found to vary; Fig. 128*e* is a typical curve showing how the current into the plate varies with the grid-potential. The abscissae are the amounts in volts by which the potential of the grid exceeds that of the negative end of the filament, the ordinates are the corresponding currents (in microamperes) flowing into the plate from the battery B_3.

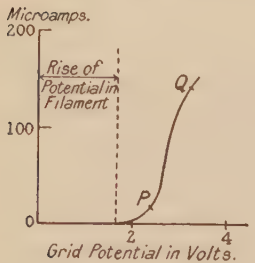


Fig. 128 *e*.

It will be seen that this curve has the same form as that for the crystal detector (p. 191*d*); if we adjust the steady potential of the grid to the value corresponding to the point P, and then create an oscillating P.D. in the coil K, so that it is superimposed on this steady P.D., we shall get as before an increase of 'average' current flowing into the plate.

It is not difficult in this case to see reasons for the peculiar features of this curve. The white-hot filament emits electrons (see p. 186); so long as they stay in the space round the filament they will by their

repulsion prevent any more from being emitted. If the grid potential is not higher than that of the positive end of the filament, the electrons will not be attracted away from it; as soon as the potential of the grid is raised slightly above that of the filament the grid begins to attract electrons, others are emitted from the filament, and a continuous stream of them passes from filament to grid, forming an electric current round the circuit through E and K. Some of these electrons pass between the coils of the grid and reach the plate; so a small current flows from B_3 and A to the plate. These electrons also collide with molecules of the gas between grid and plate, breaking them up (as described on p. 190) into additional electrons and positive

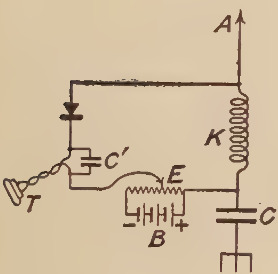


Fig. 128*f*.

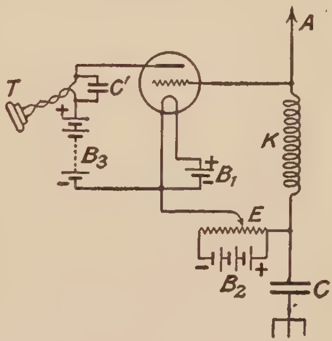


Fig. 128*g*.

ions. These electrons pass to the plate and so increase the plate-current; the positive ions go towards the grid, since it is at a lower potential than the plate, and some of them go between its coils towards the filament; the cloud of these positive ions approaching the filament attracts still more electrons out of it. This cumulative effect accounts for the steep rise of plate-current after the point P in Fig. 128*e*.

230. Use of rectifying detector in the receiving circuit. The simplest plan for using either crystal detector or valve for detecting the electric oscillations in a receiving aerial is to substitute a telephone receiver for the ammeter A, and connect one end of the coil to the aerial A, the other to one plate of a condenser C, the other plate of which is earthed; the connections are shown in Fig. 128*f* (for a crystal detector) and Fig. 128*g* (for a three-electrode valve). T is the telephone receiver; in practice it is advisable to put a small con-

denser C' in parallel with it, since otherwise the resistance, self-induction, &c., of the telephone magnets are sufficiently large to prevent the oscillations of P.D. from reaching the detector. The condenser permits this to occur without interfering with any steady currents through the telephone.

Before a train of wireless waves strikes the aerial the steady current produces a displacement, but no vibration, of the diaphragm of the telephone; no sound is therefore heard in the telephone. While a train of such waves is flowing in, the oscillations induced in the aerial produce an oscillating P.D. along the coil K, which affects the detector as described above; therefore so long as the train lasts, the average current through the telephone is increased. Hence at the beginning and end of this train a displacement of the telephone diaphragm will take place, owing to the change in the current through its magnet, and a small click will be heard. As these trains were started by separate sparks from the induction coil of the sending system, which we saw (p. 191*b*) might occur 20 or 30 times a second, the clicks will be infrequent enough to be audible. If an alternating current dynamo is used instead of an induction coil at the sending station, the trains of waves can be produced more often, say 250 or 500 times a second, and the clicks will then merge into a clear musical note in the receiving telephone, which will continue so long as the sending key is held down.

231. The following diagrams may be helpful; they represent in a conventional way, and not to scale, two of the trains of oscillations in each of the circuits already described:

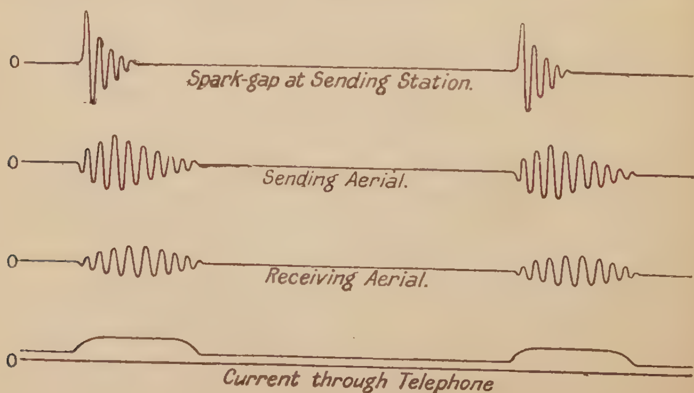


Fig. 129.

232. Other uses of the three-electrode valve. In addition to its use for 'rectifying' the oscillations in the receiving aerial in order to make the signals audible in a telephone, the three-electrode valve can be used as a relay (see p. 136) for magnifying the high frequency oscillations in the aerial before they are rectified by a second valve, or for magnifying the changes of current produced by a valve used as a rectifier. A number of such relays can be used in series, so that the signals can be amplified sufficiently to be heard through a large room. It forms such a perfect relay that it can be used for the small and rapid vibrations which occur in transmitting human speech by a telephone, and it makes wireless telephony possible.

A three-electrode valve can also be used as a generator of high frequency oscillations, taking the place of the induction coil in the sending system.

PART III

ELECTROSTATICS

CHAPTER I

Attraction and Repulsion

Experiment 76. Get a short thick stick of sealing-wax, and put on the table a pinch of bran, or some other light material, such as little pieces of paper, or of cotton about an eighth of an inch long.

Try whether the sealing-wax has the power of attracting the bran. Then rub the wax briskly on your coat-sleeve, or with a piece of dry flannel, and put it near the bran. Note what happens.

233. The fact that some bodies after being rubbed with cloth are endowed with the property of attracting others, was known to the ancients, but the name of the discoverer has not been handed down to us. Thales of Miletus is said to have known it in 600 B. C., and Theophrastus (B. C. 321) and Pliny (A. D. 70) mention this power with regard to Amber, the Greek name for which is ἤλεκτρον. In consequence of this, Dr. Gilbert, a physician of Colchester (1540–1603), who may be considered as the founder of the science with which we are to deal, gave the name of Electricity to the cause of this attraction. He determined by experiment which bodies would, and which would not, acquire the property.

Experiment 77. Repeat Experiment 76 with an ebonite * ruler, and with a piece of metal, and note the results.

Experiment 78. Gilbert tested substances by putting them near a light metal needle balanced on a pivot; you can in the following way test the power of the rubbed sealing-wax or ebonite to attract a heavy object. Balance a metre measure on the glass of a watch laid face up on the table, or on the bottom of a round bottom flask supported in a retort stand. Present the rubbed

* Ebonite consists of a mixture of india-rubber and sulphur, heated together under pressure.

part of the wax to the end of the metre measure in such a way as to drag it round horizontally. You will find that the wax exerts a power of attraction through some little distance, but that the attraction gets weaker if the distance between the bodies is increased. Determine roughly the greatest distance at which the wax can move the measure.

EXPERIMENT 79. You must now find out whether the wax is attracted by the other body; the attraction is too feeble for you to be able to feel it when you hold the wax in your hand.

Rub the wax or ebonite and hang it up in a wire stirrup suspended by a piece of thread from a stand, as in Fig. 130. Present to the end of the wax that has been rubbed, any objects you have at hand, including your finger, and observe whether they attract the wax.

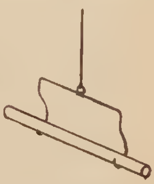


Fig. 130.

We see then that there is a force of attraction between a body 'charged with electricity' and one not so charged, each attracting the other.

234. EXPERIMENT 80. **Action of one charged body on another.** Hang up a piece of sealing-wax after it has been rubbed. Try, by putting your finger near its end, whether it is sufficiently charged.

Excite another piece of sealing-wax by rubbing it, and test its power of attracting the first piece. In doing this you must guard against having one piece much less strongly charged than the other, for then it might behave as an unelectrified body. If, however, you bring the electrified part of the second *slowly* towards the electrified part of the first and notice what happens *first*, you will not be misled.

This experiment will show the existence of a repulsion between two *charged* pieces of wax.

EXPERIMENT 81. Find out whether a piece of ebonite rubbed with flannel attracts or repels a piece of sealing-wax rubbed with flannel.

235. Pith-ball electroscope. It will be found convenient to have an instrument, which we will call an **electroscope** *, by which

* From ἤλεκτρον, and σκοπέω, I perceive.

we may test the electrical condition of a body. The simplest form consists of some light object, such as a round ball of elder-pith (which is sometimes gilded by covering it with gum and rolling it in a gold-leaf), hung from a stand by a piece of silk threaded through it. The stand should be partly of ebonite, for reasons which will be understood later. We may use a thin rod of ebonite like a penholder, from one end of which the silk hangs, the other end being clamped in a retort stand, as in Fig. 131 (*A* being the jaw of the clamp, *B* the ebonite rod, *C* the silk, and *D* the pith-ball).

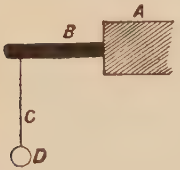


Fig. 131.

EXPERIMENT 82. Bring an electrified rod of ebonite near the pith-ball, and note the result. Let the ball touch the rod, and note the result.

The repulsion of the pith-ball suggests (in view of Experiment 80) that it has obtained a charge of electricity from the ebonite. Note that it had to roll about on the ebonite in order to collect the charge; contact at one point only removes the electricity at that point.

236. 'Non-electrics.' Dr. Gilbert concluded from his experiments that, among many other substances, metals were not capable of being electrified by friction (cf. Experiment 77), and he called them 'Non-electrics.' It was found, however, by Stephen Gray, F.R.S. (1696–1736), that such substances possess the power of conveying electricity from one substance to another, while substances such as sealing-wax do not possess this power. It is reasonable then to suppose that electricity may be produced by rubbing a metal, but that if so, it is conveyed away as fast as it is produced.

EXPERIMENT 83. Take a brass ball mounted on the end of an ebonite rod; rub the ball on a piece of dry warm flannel or cat-skin, taking care not to touch the ball with your fingers. Present it to a pith-ball electroscope, and so determine if the brass has been electrified by friction.

A brass ball so mounted is most convenient for giving a charge of electricity to an electroscope.

Substances which allow electricity to pass through them are called *Conductors*, those which do not are called *Insulators* (from Insula, an island).

EXPERIMENT 84. **Two kinds of electricity.** Charge a pith-

ball electroscope by means of a rubbed piece of sealing-wax or ebonite, so that the pith-ball is repelled on again bringing up the charging-rod.

Now rub a glass rod * with a silk handkerchief. Present the excited glass rod to the charged pith-ball and compare the action on the pith-ball with that produced by excited sealing-wax.

237. M. Du Fay, of the French Academy of Sciences (1699–1739), first noticed this difference in the behaviour of glass and sealing-wax. He saw that the electricity produced on glass must be of an opposite kind to that on sealing-wax, and called the former *vitreous* electricity and the latter *resinous*. He found that 'vitreous' electricity was produced on glass, rock crystal, precious stones, hair of animals, wool, &c.; and 'resinous' on amber, copal (used for varnish), silk, paper, &c.

It will have been observed in Experiment 84 that after the pith-ball, which was first charged with resinous electricity, has touched the glass rod charged with vitreous electricity, it is repelled; showing that bodies charged with vitreous electricity repel one another (just as is the case with bodies charged with resinous electricity), but that if two bodies are charged with different electricities they attract one another. In other words

Bodies charged with like electricities repel one another.

„ „ „ unlike „ attract „ „

Also we may deduce from the same experiment that the vitreous electricity was able to destroy the resinous electricity previously on the pith-ball. If the experiment be repeated, starting by electrifying the pith-ball with vitreous electricity and then bringing up charged sealing-wax, the same phenomena will occur, showing that either kind will destroy the other.

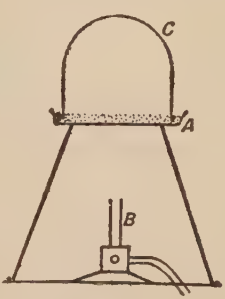


Fig. 132.

* Both glass (*lead* glass, not soda glass, must be used) and silk must be warm, or it will be found that the glass will not be 'excited'; in all these experiments it is much better that the rubbers should be warm, but there is usually no need to heat ebonite and of course sealing-wax must not be heated. A convenient warming arrangement is a sand bath *A*, heated by a gas-burner *B*, with an arched tin cover *C* over it; glass rods are laid on the sand and the rubbers put on the tin roof.

238. Since it will be found a simple matter to produce resinous electricity on glass by using a suitable rubber, Du Fay's names were not well chosen, and *Positive* and *Negative* are now always used instead of Vitreous and Resinous respectively.

These names have the advantage of suggesting the fact that a combination of the two electricities is destructive to both.

SUMMARY OF CHAPTER I.

Sealing-wax and ebonite, after being rubbed with wool, acquire the power of attracting other bodies not so treated, and are themselves attracted.

A body charged with electricity repels another body charged in the same manner.

Metals do not show these effects unless they are mounted on an insulator, since they conduct the electricity away as fast as it is formed.

Glass rubbed with silk behaves in an opposite manner to ebonite rubbed with flannel. (But both attract *unexcited* bodies.)

The electricity produced on glass by rubbing with silk is called Vitreous or Positive; that on ebonite by rubbing with wool, Resinous or Negative.

Bodies charged with like electricities repel one another.

Bodies charged with unlike electricities attract one another.

CHAPTER II

ELECTROSCOPES

THE repulsion between two similarly charged bodies enables us to construct electroscopes more convenient than the one used hitherto.

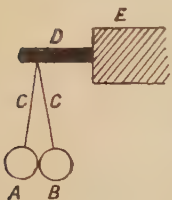


Fig. 133.

239. Double pith-ball electroscope. Two pith-balls (A and B, Fig. 133) are hung side by side by pieces of thread or cotton (C), *not silk*, from an ebonite rod D, supported in a clamp E. If either of the pith-balls is electrified, part of the charge will pass to the other, either by direct contact or by means of the cotton which is a conductor, and the two balls will repel one another. The charge cannot pass away, since the ebonite is an insulator, and the balls will remain at some distance apart so long as they are charged.

This is a rough arrangement for estimating, by the separation of the pith-balls, the existence and amount of the charge at any point of a large conductor to which the cotton carrying the pith-balls is attached.

240. Gold-leaf electroscope. This is a much more sensitive instrument. It consists of a glass bottle A (Fig. 134) or bell-jar

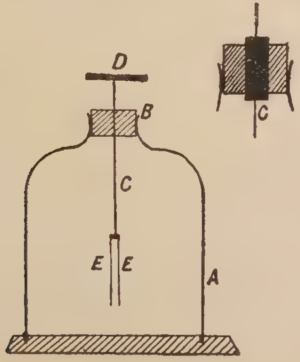


Fig. 134.

mounted on a wooden stand ; this acts as a support, and keeps away draughts. In the neck is an india-rubber bung, through which passes a thick wire C*, with its top ending in a metal plate or knob D, and having a metal cross-piece at the bottom. To each side of this is attached a long strip of gold-leaf, so that the strips hang face to face at a small distance apart.

If a charge of electricity is given to D, it spreads to the gold-leaves and makes them separate, just as the pith-balls do in the electroscope described in Art. 239.

241. Modifications of the electroscope. (1) If extreme sensitiveness is not required, Dutch metal, or aluminium-foil, may be substituted for gold-leaf.

(2) Vertical strips of tin-foil are often gummed to the inside or outside of the bottle at intervals all round it ; these are connected together by a strip of tin-foil at the bottom and arrangements are made for attaching to it a wire. If this wire is connected to some gas or water-pipe running down to the ground, the gold-leaves will be guarded from the action of any electricity except that reaching them through the knob, as will be seen on p. 205.

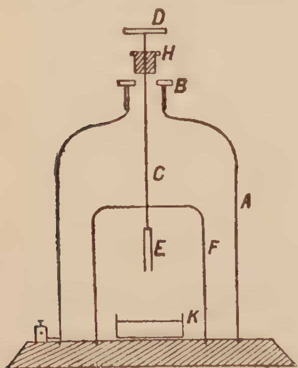


Fig. 135.

(3) Since gold-leaf is very fragile, strips of tin-foil may be fixed to the glass inside and connected to this wire reaching the ground. If too large a charge is given to the knob, the leaves, instead of being torn from their support by their violent repulsion, swing apart till they touch this tin-foil, when they lose their charge by conduction and collapse again.

(4) In order to improve the insulation of the leaves, the wire supporting them may be carried on an arch of glass rod F (Fig. 135), which rises from the base. The wire C does not then touch the neck B of the jar when the electroscope is in use ; but a cork H can slide

* It is much better if the wire passes through a hole in a rod of ebonite which itself passes through the bung, so that the wire does not touch the bung.

down the wire to close the mouth B when the instrument is put away, to exclude dust and damp air. On the base is put a dish K containing concentrated sulphuric acid. This possesses the property of absorbing water-vapour from the air, so that the air in the bottle is kept dry, and then the glass rod F acts as a perfect insulator (see p. 195).

(5) A small graduated scale may be mounted so as to stand behind the gold-leaves and enable the angle through which they diverge to be roughly estimated, thus measuring the extent to which the electroscope is charged. A small mirror should be added in the plane of the scale so that 'parallax-error' may be avoided (cf. p. 24 *c*).

242. Conducting-power of some substances. A gold-leaf electroscope can be used to compare roughly the powers of conducting electricity possessed by different substances.

EXPERIMENT 85. Charge a gold-leaf electroscope, by rubbing an insulated metal ball on a piece of dry flannel and touching the knob with the ball. If this does not produce a sufficient divergence of the leaves, repeat the operation until it does.

Stretch a piece of cotton, about a foot long, between your two hands and touch the knob with the middle of the length. Watch the gold-leaves: if they do not collapse at all, cotton is an insulator; if they collapse immediately it must be a good conductor; if slowly, a poor conductor. Note which does happen.

Repeat the whole operation with a piece of white silk, of metal wire, and of thread, with a strip of paper, pieces of flannel and cat-skin; with the wood of a lead pencil; with a glass rod or tube. Arrange these substances as nearly as you can in order of merit as insulators.

EXPERIMENT 86. Repeat Experiment 85, first using a dry piece of white silk, then repeat after moistening the whole length of silk from your finger to the knob.

243. Methods of insulation. This experiment will show you that water is an excellent conductor, and the thinnest film over the surface of any insulator will ruin its power of insulating. Glass (in itself an extremely perfect insulator) is a substance which has an undesirable tendency to collect such a film of moisture from the air, and this tendency makes its use in electrical apparatus most undesirable. It can be overcome by keeping the glass warmer than

the air, and of course by keeping the air dry as was explained on p. 199; glass should also be kept scrupulously clean from grease. Dry glass (*lead* glass, not soda glass) is an excellent insulator, and if it has been recently covered with a layer of good varnish it forms good insulating supports. The present cheapness of ebonite makes it unnecessary to use glass, except in cases where we have to produce positive electricity by rubbing it (when of course it cannot be varnished), or when we need a transparent insulator.

Care must be taken not to heat any apparatus containing ebonite, since it becomes plastic when hot.

In order to ensure the dryness of all insulators, it is very convenient to have a small radiating gas-stove on the table, in front of which the experiments are carried out.

245. The electricity on the rubber. We have hitherto experimented only with the solid body rubbed; we must now determine whether anything happens to the rubber. For this purpose it is most convenient to use an ebonite ruler on which a cap of flannel, about three inches long, fits fairly tightly. This cap must be provided with a tassel of silk, by which it may be pulled off without touching the partially conducting flannel.

EXPERIMENT 87. Take the ebonite ruler and see that it is not charged before you begin the experiment. If it is, you must remove the electricity, either by passing the ruler gently through your hand (taking care to touch all points on the ruler, but not to excite the ebonite by friction with your hand) or by passing the ruler through a Bunsen flame, which discharges it completely. Test the success of this by means of a single pith-ball electroscope, uncharged.

Fig. 138.

Now put on the cap, which should be warm and dry, and rub the ruler round inside it, gripping the cap tightly.

Without removing the cap from the ruler, test whether any electricity has been produced, using the uncharged pith-ball electroscope.

Charge the pith-ball with either kind of electricity by means of another rod and rubber.

Now pull off the cap by help of the tassel, and present first the ruler, and then the cap, to the charged pith-ball. Thus you determine

whether there is electricity on both ruler and cap, and if so the kind on each.

By experiments like this we are led to conclude that *whenever through the rubbing of one body on another we produce one kind of electricity, we produce at the same time an equal quantity of the opposite kind.*

246. Theory as to the nature of electricity. During the last four or five years of the nineteenth and the early years of the twentieth century, a theory has been elaborated to account for the observed facts in electrostatics, current electricity, magnetism, and optics; it is chiefly based on the researches and discoveries of Sir J. J. Thomson, of Cambridge, and the school of physicists which he created there. It does not pretend to explain what electricity actually is; there must be some simple fundamental thing in the universe which we cannot explain, and whose existence we must accept, using it as the starting-point for our explanation of the more or less complicated phenomena which we observe.

According to this theory all substances consist of very minute particles called Atoms; there is a limited number (ninety-two) of different kinds of atoms, but all of one kind are exactly similar to one another. Each atom consists of a 'nucleus' and one or more (up to ninety-two) still smaller particles, called electrons; each electron contains a quantity of negative electricity, which is the same for all electrons. The electrons in every different kind of atom are identical, but the nucleus differs in different kinds of atoms; different atoms are of different weights and contain different quantities of electricity. This electricity is positive, and its quantity is just sufficient to balance or neutralize the negative electricity on the electrons which, with the nucleus, make up that atom.

For instance, the atom of Hydrogen (which is the lightest atom known) contains one electron, together with a nucleus weighing about 1,800 times as much as an electron, and having a charge of positive electricity numerically equal to that on an electron. An atom of gold contains 79 electrons, together with a nucleus weighing about 197 + 1,800 times as much as an electron, and having a charge of positive electricity equal to that on 79 electrons.

When a substance is in the liquid or gaseous state its atoms wander about throughout it; they are usually grouped into 'molecules,' each containing two or more atoms of the same or different kinds. When the substance is a solid the atoms do not move about in this way,

but remain in the same place in the mass; some, at any rate, of the electrons are not fixed, but can leave their own atoms and migrate to a neighbouring one. As these electrons contain electricity, their freedom to move about in the mass accounts for the possibility of the movement of electricity through it. In some substances (conductors) the electrons can move freely from atom to atom; in others (insulators) they cannot do so at all, or only very little.

When the surface of a piece of flannel is brought into close contact with that of a piece of ebonite, by rubbing them together, the electrons in the surface atoms of the flannel pass over to the surface atoms of the ebonite; this produces a negative charge on the ebonite, and a positive charge on the flannel, since the positive charges on the nuclei on the surface of the flannel are no longer neutralized by electrons.

Further information on electrons and the conduction of electricity will be found on p. 169 and in Chap. XVI, p. 184.

CHAPTER III

Induction

247. Experiment 88. Support a half-metre measure (*B*, Fig. 139) horizontally on an insulator, about a foot above the table. A convenient way to do this is to pile blocks (*C*) of wood, and put a block of paraffin wax *D* on the top. This is a very good insulator.

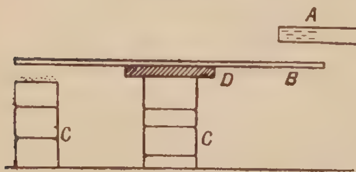


Fig. 139.

Under one end of the metre measure, make another pile of blocks, so that the top is about 2 cms. below the half-metre measure, and put a pinch of scraps of paper or bran on the top. Hold a charged ebonite ruler *A* along the other end of the half-metre measure, parallel to but *not touching it.*

Note whether anything happens to the scraps of paper. Remove *A*, and note whether the action continues. Has the metre measure acquired any charge, temporary or permanent?

EXPERIMENT 89. Get a cylinder with rounded ends, about a foot long and an inch or more in diameter, made of metal or of wood covered with metal foil. Support this by an insulator; it will be simplest to hang it up vertically, by dry white silk attached to its end by a drawing-pin. Bring near to one end of it the charged part of a highly charged ebonite ruler (do not let them touch one another); hold the ruler so that it is about half an inch from the cylinder.

Now take a pith-ball hung by a piece of dry white silk, charge it with electricity by letting it touch the charged ruler, and bring it near to various parts of the cylinder, noticing in each case whether it is attracted or repelled. Draw a diagram such as Fig. 140, marking it with + or – wherever you perceive the existence of either electricity. Take away the charged ruler and see whether the cylinder retains any electrical charge.

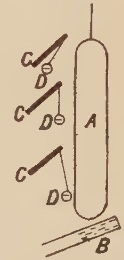


Fig. 140.

The experiment should be repeated with a positively charged body at *B*.

248. We saw in Experiment 82 that electricity can be transferred to one body from another when they touch; we now see that merely bringing a charged body near to a conducting body produces charges on the latter. These are, however, of opposite kinds on the two ends, and they flow together and neutralize one another when the charged body is removed. These charges are said to be *induced* by the charged body.

249. When you were performing Experiment 85, you may have noted the fact that the gold-leaves of the electroscope began to diverge before the knob was touched by the charged brass ball. You can now see that this was due to induction, since the knob, wire, and leaves of the electroscope form a conductor like the cylinder of Experiment 89, and when the charged ball (*A* in Fig. 141) is brought up to the knob of the electro-

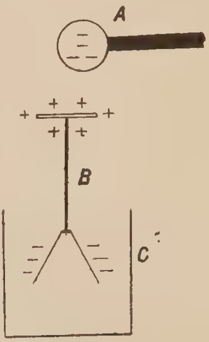


Fig. 141 *.

* In Fig. 141 *B* is the usual diagrammatic way of representing a gold-leaf electroscope, *C* being the cage of tin-foil pasted on the glass.

scope, + electricity is induced on the knob, and − on the leaves; these being similarly charged repel one another, and the divergence increases as *A* is brought nearer.

250. If a charged body, either a conductor or an insulator, is brought near to an uncharged insulated conductor, in addition to attracting it, it separates out some of the inexhaustible store of the two electricities postulated on the two-fluid theory. It attracts to the near end electricity unlike that on the inducing charged body, and repels to the further part of the body electricity of the same kind as on the inducing body. Looking at it in the light of the modern theory, if the charged body contains an excess of negative electrons above the normal (i. e. if it is − charged), it repels some of the negative electrons on the conductor to the further end, giving it a − charge, and leaves a defect at the near end, or gives it a + charge. The opposite happens with a + charged body as inductor.

Without considering any theory, the result of bringing a charged body near to an uncharged insulated conductor is to induce unlike electricity on the nearer parts of the conductor, and of the same kind on the further parts, as in Fig. 142.

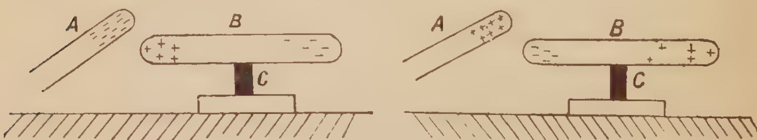


Fig. 142.

Here *A* is the charged body, *B* the conductor on an insulating stand *C*.

251. We have seen that induction can take place through air; we may now test other materials.

EXPERIMENT 90. Take a gold-leaf electroscope, uncharged, and a charged body; bring the charged body near to the knob and see that the leaves diverge properly. Remove the charged body. Take a sheet of ebonite or vulcanite, uncharged, and hold it over the knob; then bring up on the far side of the sheet the charged body, and see if the gold-leaves are affected. If so induction can take place through vulcanite.

Similarly test sheets of paraffin, tin, glass, paper, and any other material you can get in sheets.

A material which permits of Induction taking place through it is called a *dielectric* *; you will observe that a conductor is not a dielectric †. This explains the utility of the cage of tin-foil or wire-gauze recommended for electroscopes on p. 198, since it prevents the leaves from being affected by the inductive action of charges outside the electroscope, except viâ the knob.

252. Apparent action of a metal as a dielectric.

EXPERIMENT 91. Support a sheet of tin-foil on a sheet of glass, so as to leave a margin of glass round the edge of the foil; a 'Franklin's Pane,' as described on p. 248, will do well. Hold this by the *glass*, taking care not to touch the foil, and as in Experiment 90, test whether it is a dielectric. Then hold it so that your finger touches the foil, and again test.

Try to explain why electric action *seems* to take place through the metal, by considering the charges induced on the foil. When you have done Experiment 94 you ought to be able to explain why these charges do not affect the gold-leaves when the finger touches the foil, assuming (as is the fact) that metals are not dielectrics.

You will now see how important it is that the cage surrounding the gold-leaf electroscope should be connected to the earth either by your finger or a wire, in order to prevent inductive action on the leaves except through the knob.

253. Effect of induction on a body already charged.

EXPERIMENT 92. Take an electroscope already slightly charged with, say, negative electricity. Bring near to its knob a negatively charged body. Note the effect, and draw diagrams such as Fig. 143. This shows that induction takes place in the same way on a charged as on an uncharged body. Bring near to the same electroscope a positively

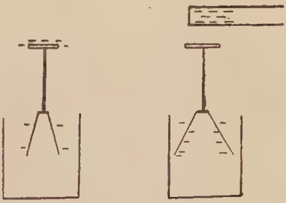


Fig. 143.

* This term was first used by Faraday in 1837.

† Do not confuse the two ideas of *electricity passing through* a conductor, and the *effect of* electricity *on other bodies* being transmitted through a non-conductor.

charged body, watching the effect as you bring it slowly up from a considerable distance until it is quite close to the knob. Draw diagrams and account for the results.

If we have to determine the kind of electricity with which a body is charged, the best way is, obviously, to bring it near to the knob of an electroscope already charged with electricity of *known* sign; if the leaves diverge more widely, the charge on the body is the same as that on the electroscope; if they *begin* by collapsing, it is unlike.

254. Production of permanent charges by induction. Suppose that we are able to cut in half an elongated body, such as the cylinder in Experiment 89, while it is still under induction, without affecting the charges on it, it might seem reasonable to suppose that we should be left with + electricity on one half and − on the other; but it would be very unsafe to assume this without trying the experiment, in view of what happens when a magnet is broken in two (see p. 10).

EXPERIMENT 93. Take two conductors on insulating stands; such as brass door-knobs on ebonite rods. Set up the knobs (*B* and *C*, Fig. 144) so that they touch and form one long conductor; bring up the charged body (*A*) near one of the knobs (*B*), and *while A is still near B*, pull *C* away from *B* by means of its insulating stand. Then take away *A*, and bring *B* and *C* separately up to the knob of a charged electroscope and investigate the charges on each.

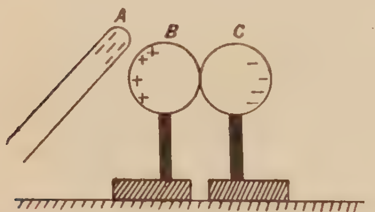


Fig. 144.

By repeating such a process as this with other knobs we can, without further friction or destruction of the original charge, obtain an indefinitely great quantity of electricity; and it is the basis of the modern machines for producing 'statical electricity.'

255. Effect of 'earthing' a body under induction. To connect a body with the earth by means of a conductor is technically called *earthing* it; it may best be done by attaching a wire to a gas or water-pipe, and to the body, but since wood is a partial conductor it is often sufficient to put the body on the table. The human body and boot-soles, especially if wet, are sufficiently good conductors, so that the quickest way to earth a body is to touch it with a finger.

EXPERIMENT 94. Take an insulated elongated conductor and bring near to one end a charged body. While the conductor is under induction, earth it, and remove the connection with the earth *before* you remove the inducing body. Test the conductor for electricity, and compare its sign with that of the electricity on the inducing body. Determine whether the sign of the electricity left on it is affected by varying the point at which the conductor is earthed.

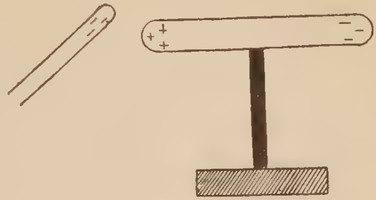


Fig. 145.

The point left unexplained in Experiment 91 should now be cleared up.

256. Owing to this behaviour, the electricity attracted to the inducing body, which is situated on the parts of the conductor nearest to the inducing body, is usually said to be *bound*, since it does not escape when an opportunity is offered; the opposite electricity is said to be *free*. It is especially worthy of note that the free electricity takes advantage of any route to the earth, even if it involves an approach towards the electricity of the same kind on the inducing body.

The student will observe that the electricity which is 'bound' by the charged body becomes free when that body is removed to a distance, and that it can then flow to any part of the conductor in the same way as a charge produced by friction.

257. Lines of Force. Since the charge on the inducing body 'binds' the induced charge of the unlike electricity, there is some definite connection between them through the dielectric. This is often represented in a diagram by a series of lines, each starting from a point on the surface of the inducing body and ending on that of the body under induction. Each line is supposed to connect one particular element of the charge with the charge which it induces. Since there is an actual force of attraction between these two, such lines are called 'Lines of Force' or 'Lines of Induction.' The idea of such lines originated with Michael Faraday, Professor at the Royal Institution, and they have been found of immense use in giving a definite physical idea of electrical actions; they lead us away from the still doubtful

theories as to what electricity is towards the consideration of what actually takes place in the dielectric.

258. The first question that arises is, should these lines be drawn *straight* from one charge to the other? Faraday investigated this question with great care and fulness *, since he saw that if the lines are curved, the action can only be explained by the existence of a medium between the bodies. Through this the action proceeds as intelligibly as the manner in which the pressure on the pedal of a bicycle is transferred to the road; without it, we cannot imagine the process.

259. These 'lines of force' can be shown experimentally to be curved, but their actual track in any given case is not an easy matter to determine. However, an approximation to the truth is better than nothing; so the student should mark in his diagrams of experiments in which charges are 'bound' together by induction, lines of force connecting these charges, taking as a guide the distribution of the 'lines of force' between magnets.

Thus Fig. 142 might be completed as in Fig. 146. It will be seen that lines of force are drawn from the 'free' charge, and are supposed to continue until they reach the walls of the room or other 'earth.' Another charge must be induced on the walls by this 'free' charge, with which the 'free' charge on *C* will combine, if a chance be given to it. As a matter of fact, all we mean by a 'free' charge is one bound by a charge on the earth, instead of on an insulated conductor or insulator; the possibility of a charge of either kind of electricity being produced without the simultaneous production of an equal and opposite charge has already been disproved.

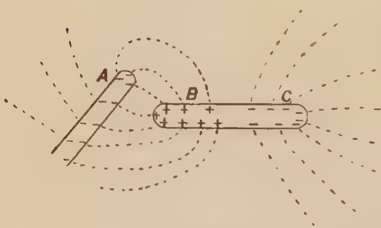


Fig. 146.

EXPERIMENT 95. **To charge an electroscope by induction.** Take an uncharged gold-leaf electroscope. Bring near to its knob a body charged with electricity, until the leaves diverge widely (but not so far as to endanger them, or to make them touch the tin-foil

* See his *Experimental Researches*, especially Nos. 1215–1231.

cage, if there is one). Holding the charged body in the same position, touch the knob with the finger; remove it, and *then* remove the charged body. Note what happens at each operation; draw

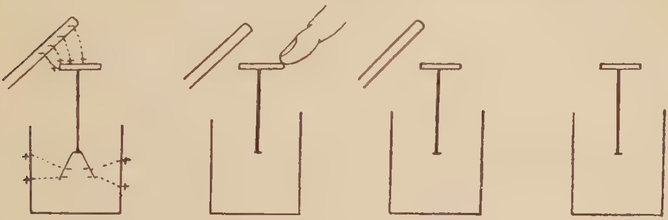


Fig. 147.

a series of diagrams as Fig. 147, putting in the positions assumed by the leaves; then add + and − and lines of force to the electrified parts in each diagram, as is done already in the first.

260. It will be seen that the *final* charge on the electroscope is opposite in sign to that on the charging body, and that, with a given charged body, we can by this process charge our electroscope just so highly as we please. If the student has ever attempted to charge a gold-leaf electroscope by *conduction* with the electricity from a glass or ebonite rod, he will appreciate the advantages of this method by induction. Hitherto the gold-leaf electroscope could only be *negatively* charged by conduction from a rubbed insulated metal ball, or by gently beating the metal knob or plate of the electroscope itself with a piece of cat-skin; now, it may be charged positively by induction from the same ball, or from such a non-conductor as ebonite, or it may be charged negatively, by conduction from the metal, or by induction from a rubbed glass rod.

The method by induction is most useful, but it must be carefully borne in mind that *an electroscope charged by induction carries electricity of the opposite sign to that on the charging body.*

261. The electrophorus. An electrophorus (ἤλεκτρον, and φέρω, I carry) is an improved form of the device used in Experiment 92 or Experiment 93 for producing supplies of electricity by induction from a body charged once for all by friction.

The inducing body consists of a sheet of ebonite laid on a sheet of metal, or of a disk of some resinous material cast in a shallow metal dish. This disk is electrified negatively by being rubbed with fur.

On this can be placed a flat disk of metal, which is fitted with a non-conducting handle, usually of ebonite; this is called the *cover.*

If a sheet of tin-foil were laid on the electrified disk and pressed into close contact all over it, or if both disk and cover were 'true planes,' and they were pressed together closely enough to exclude any film of air, then on raising the metal the disk would be found entirely discharged. As a matter of fact, although both disk and cover are made ordinarily flat, without taking special precautions, it will be found that, if the cover is pressed down on the disk by the handle and then raised, it will take away a very small charge indeed, and the disk will have lost very little. This happens because they only touch at a few points, and only those points lose their charge, since ebonite is a non-conductor.

We may then represent the condition of affairs by Fig. 148, in which

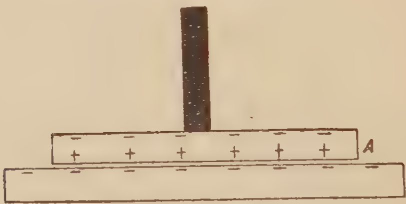


Fig. 148.

A is the cover, and *B* the ebonite disk. The – charge on *B* induces + on the lower surface of *A* and free – on the upper surface.

If we now touch the cover *A* with the finger (Fig. 149), the free –

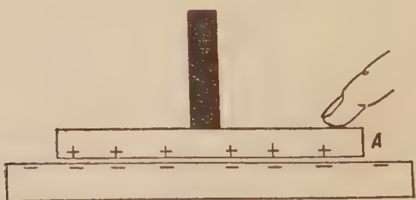


Fig. 149.

electricity will go to earth, leaving the + bound.

On removing the finger and raising the cover by the insulating handle

(Fig. 150), this + charge becomes free (as it did in Experiment 93), and can be transferred to any other body by conduction; while the original – charge on the ebonite disk remains unaffected. This process may be repeated, after discharging the cover, as often as is desired until the charge on *B* leaks away in the ordinary course.

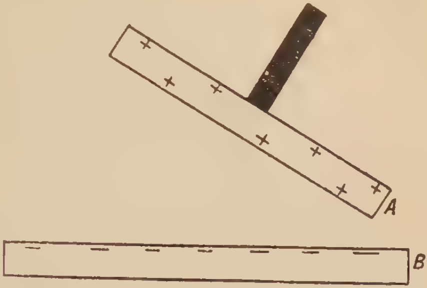


Fig. 150.

262*. This explanation of the action of the electrophorus is very simple, but not quite complete, since the 'sole,' or metal plate, on which the ebonite disk is placed, plays an important part. We will now consider this point. Before the cover is first put on, the – electricity produced by friction on the top of the ebonite disk will induce a + charge on the nearest conductor, which is the sole *C*, as in Fig. 151. When the metal cover is put on, the – electricity on the disk will induce a + charge in the cover in preference to the sole, since it is nearer; but the free negative, produced by this induction, on the upper surface of the cover will still keep the + charge on the sole, so that there will be two pairs of 'bound' charges, represented in Fig. 152.

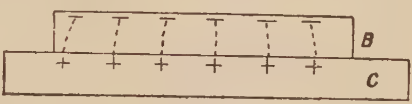


Fig. 151.

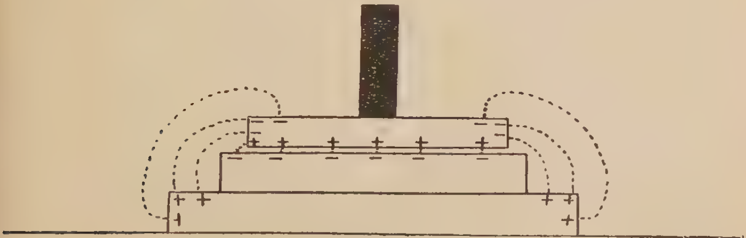


Fig. 152.

The inner pair hold each other bound, and so do the outer pair.

If we now connect together the sole and the cover, the outer pair of charges rush together and neutralize one another. This takes place even if the cover is merely touched with a finger, since that establishes a connection through the body, the floor, and table, which permits the two charges to reach one another.

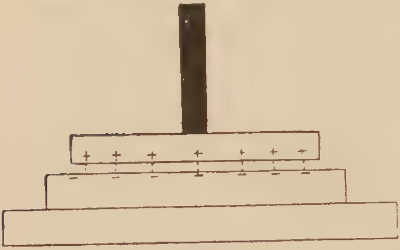


Fig. 153.

We shall then have left but one pair of charges as in Fig. 153. Since the disk is a non-conductor, neither of these charges can be affected by the contact which discharged the cover; and, until we lift up the cover by the insulating handle, the charge on it will be bound to the lower surface by the immovable charge on the disk. If, however, we now carry the cover by means of the handle out of the sphere of influence of the charge on the disk, the + charge on the cover will be free to spread itself over the cover, and to pass by conduction from the cover if it be touched by any other body. Thus we have succeeded in charging the cover by induction with a free charge practically equal to that on the disk, and much more available since it is on a conductor.

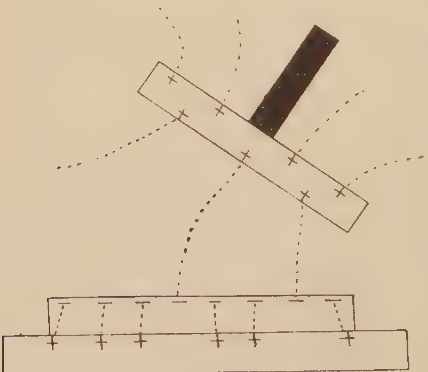


Fig. 154.

As the cover is removed the charge on the disk will call up from the earth by induction a fresh + charge on the sole, and the state of affairs will be as in Fig. 154; when the cover is discharged, the cycle of operations can be repeated, except that there is no necessity for again exciting the disk.

Experiment 96. Warm the disk and handle of an electrophorus, and excite the disk with a warm piece of fur.

Place the cover on the disk, touch the cover with the finger, remove the finger and lift up the cover by the insulating handle.

Put your knuckle near the edge of the cover and note the result.

Charge a gold-leaf electroscope with electricity of a known sign, re-charge the cover as before and *cautiously* bring it up towards the knob of the electroscope, and so determine the sign of the charge on the cover. Does it agree with the above theory?

Never touch a gold-leaf electroscope with the charged cover of an electrophorus.

263. The process of charging the cover of an electrophorus can be made more automatic. This is done occasionally in an electrophorus but always in Voss and Wimshurst machines, which are entirely automatic.

A metal stud connected with the metal sole is made to pass through the charged disk so as to stand level with, or very slightly above, the surface of the disk. There is now no need to touch the cover each time with the finger, in order to earth it while it is in presence of the inducing charge, since this is done by the metal stud. It might seem that the metal stud would also carry away the + charge on the cover as it was being lifted away; this will not happen, since the charge is still bound by the − charge on the ebonite until it is beyond the distance at which it can pass to the stud (even in the form of a spark such as was obtained in Experiment 96.)

There will of course be no bound + charge on the cover just opposite the stud, so that the effective area of the cover will be very slightly lessened. When an electrophorus is furnished with such a stud it is only necessary to excite the ebonite or resinous cake, and then to put down the metal cover on the cake and lift it up charged.

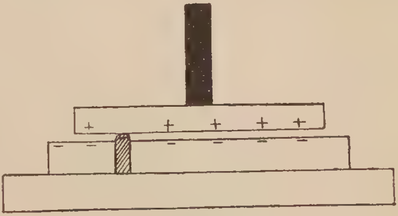


Fig. 155.

As a substitute for a stud, a strip of tin-foil may be fixed to the disk, passing round from the under side, where it will be in contact with the sole, to the upper side, where it will touch the cover. In this case it will be advisable to lift up the cover so that the part near this strip rises first.

CHAPTER IV

POTENTIAL

264. Potential of a body. In discussing the effects of heat on a body, the idea of **temperature** is found necessary; we need something of the same kind in considering the effect produced on a body by adding or taking away electricity. The word employed in this connection is **Potential**; the student will most readily grasp the meaning of 'the potential of a conductor' by recalling what he has learnt of temperature. Temperature is often defined as 'the condition of a body in virtue of which heat tends to pass from it to other bodies, or vice versa.'

The **potential** of a body may be defined as *the condition of the body in virtue of which electricity tends to pass from it to the earth, or vice versa.*

265. One body is said to be at a higher *temperature* than another if heat passes from the first to the second when they are put into communication; so, one body is said to be at a higher *potential* than another if electricity passes from the first to the second when they are connected by a conductor (such as a wire).

The earth, in the case of electricity, is taken as being the 'zero' for potential, just as melting ice is taken as the zero of the centigrade scale of temperature; if heat tends to pass from a body to melting ice its temperature is above zero, or positive, and if the reverse, it is negative. So, *if + electricity tends to pass from a body to the earth it is said to be of + potential; if from the earth to the body, the body is said to be of − potential.*

266*. Temperature is *numerically measured* on an arbitrary scale in a very arbitrary manner; the steam from water boiling under a surface pressure of 76 cm. of mercury is taken as having a precise temperature, called an upper fixed point. To this is assigned an arbitrary value, 100° C., and the degrees intermediate between it and zero are fixed by the help of an *effect* of heat on a particular body (mercury), since it is a matter of common knowledge that the addition of heat to mercury makes it expand. It is then laid down that for each one-hundredth part of the total expansion of a definite quantity of mercury, passing from the temperature of melting ice to that of boiling water, the temperature of the mercury shall be taken to have risen 1°. It is only when (and if) the student reaches a fairly advanced point in the study of thermody-

namics that he learns that there is a sound *mechanical* basis for such an assumption being made in the case of an ideal 'perfect gas' instead of mercury; and since (cf. Charles's law) even an ordinary gas expands fairly regularly when compared with mercury, the above working definition of 1° C. is found to be sufficiently accurate for the purpose of an elementary course of heat. Fortunately for the learner, he comes across the notion of degrees of temperature so often before he studies Heat as a 'subject,' that such a definition for the unit of temperature does not succeed in confusing his mind; unfortunately for him he does not so use potential in everyday life, and it is only by keeping firmly in mind its analogy with temperature that he will escape confusion.

267. There is no 'scale of potential,' centigrade or otherwise, but potential is ordinarily expressed in 'volts'; the number of volts by which the potential of a body is above or below that of the earth corresponds with the number of degrees above or below freezing point. For example, the potential, or 'pressure' of an electric light main is said to be 100, 240, &c., volts. The actual unit of potential is defined strictly and directly on a mechanical basis, which we will not discuss at present (but will consider on p. 265): this unit is 300 volts.

As a rough method of estimating the potential of a body we can use a gold-leaf electroscope, in much the same way as a thermometer is used to estimate the temperature of a body.

268. Just as the presence of heat in a thermometer causes the mercury to run up the stem to a greater or less extent, so we have seen that the presence of electricity in the leaves of a gold-leaf electroscope whose cage is earthed, causes the leaves to diverge more or less widely, according to the amount of electricity in the leaves. We will therefore take the divergence of the leaves of an electroscope as a *measure* of the potential of a body to which it is connected; a scale may be put behind the leaves so that potentials may be roughly compared; and as we are not tied down to any particular electroscope, we will assume that it is a small one*.

269. It is important to understand the reason why we can use a gold-leaf electroscope as a potential measurer. The potential

* Just as we must use a thermometer which is small compared to the object whose temperature is to be measured, in order to avoid affecting that temperature by the heat needed to work the thermometer.

difference between a body and the earth is merely a measure of the tendency of the electricity on the body to get to the earth; and as the gold-leaves are connected to the body, and the cage of the electroscope to the earth, the electricity on the body will try to reach the earth by that route, and will produce a bodily force on each gold-leaf, driving it towards the cage with a greater or less force according as the potential is higher or lower. We shall learn later that between two bodies at a fixed distance apart the force of electric attraction depends on the difference of potential between them; this is a deduction from the mechanical definition of potential alluded to above. The gold-leaves do not, it is true, remain at a fixed distance from the cage as their divergence changes, so that this is only a rough potential measurer.

This view, of the gold-leaves being each attracted to the cage, is much more probable than that according to which they repel each other.

270. One disadvantage attaches to the electroscope, that its leaves diverge to indicate potentials both above and below zero, a fault not shared by a thermometer. If, however, there is any doubt as to the sign of the potential, we can test it by disconnecting the electroscope (while its leaves still diverge) and bringing up a body charged with electricity of known sign, say +; the leaves will then diverge further if the potential was $+^{ve}$, and will collapse if it was $-^{ve}$.

271. The student should now carry out some experiments to familiarize himself with the use of an electroscope for the comparison of potentials.

EXPERIMENT 97. **Potential increases with charge.** Take a large insulated conductor of any shape, such as a coffee-tin on a block of paraffin, and connect it by a wire (say No. 36 copper wire) with the knob of an electroscope of which the cage is earthed. *This last condition will always be assumed unless the contrary is stated*, and further, the electroscope should be at some distance from any charged bodies.

Care must be taken that the connecting wire does not touch the table or any other 'earth.'

By means of a metal ball on an insulating handle, transfer a series of small charges from a charged electrophorus cover to the insulated conductor. Watch the electroscope to see how the potential of the conductor changes.

Notice the similarity between this and the manner in which the temperature of a body (usually) rises with the continued addition to it of quantities of heat.

272. It is convenient to have some means of connecting the electroscope to the body to be tested, without interfering with any charge that there may be on the body. The simplest arrangement for this purpose consists of a stick of ebonite having the end of a piece of thin copper wire attached to its end, the other end of the wire being attached to the electroscope.

EXPERIMENT 98. **Effect of connecting together two bodies at different potentials.** You know what occurs when two bodies at different temperatures are put under conditions in which heat can pass from one to the other, e. g. when hot water is mixed with cold, or when hot copper is dropped into cold water. You can determine whether the same occurs to the potentials of two bodies, by taking two insulated conductors charged to different potentials, connecting them by a wire and then testing their potentials.

The simplest apparatus is, as usual, the best; as conductors use two large tins (Fig. 156), standing on two blocks of paraffin in such a way

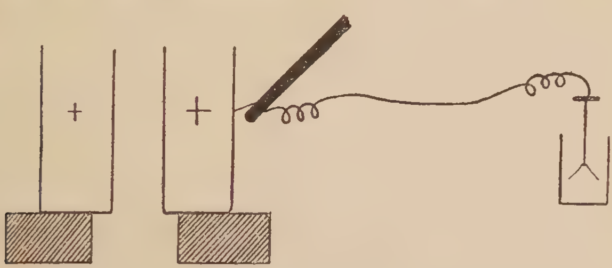


Fig. 156.

that they project slightly over the edge of the block. This makes it easy to let the tins touch when necessary by sliding the blocks of paraffin along the table.

Charge these tins, by means of an electrophorus, to widely different potentials as tested by the electroscope with its movable wire. There is no need to discharge the electroscope after each test of a potential (any more than there is to dip a thermometer in melting ice), *provided that* the electroscope leaves, &c., are small compared with the conductor, so that they do not affect its charge.

Now slide the tins into contact, separate them and test the potential of each, comparing this with its former potential and with the final potential of the other.

273. Here should be noted a point of difference between heat and electricity, which you may verify during your experiments. It takes some little time for the equalization of temperature of two bodies, even if they are in close contact, while equalization of potential is practically instantaneous, owing to the enormous speed at which electricity travels.

You have proved that two bodies in contact acquire the same potential: you can easily demonstrate, by a modification of Experiment 98, that the same happens when the bodies are connected by any conductor, even by a long thin wire.

274. Since electricity travels almost instantaneously through a conductor there is little chance of finding different potentials in different parts of the same conductor, as happens with temperature; but you should test the matter.

EXPERIMENT 99. **Potential the same throughout a charged conductor.** Lay an empty tin on a block of paraffin or other insulating stand; charge it and explore its potential at various points inside and outside the tin, by touching them with the end of an insulated wire connected with the knob of a gold-leaf electroscope.

It would appear probable, even before carrying out this experiment, that the potential would be found uniform throughout the body, because if the potential was low at any point there would be nothing to prevent electricity from flowing from the place where it was in excess until the potential was equalized. This would be suggested by the way in which heat flows in a body.

275. There is, however, a condition of things to which we have no parallel in heat, when charges are *induced* in different parts of a body. Here we know that we may have a considerable accumulation of + electricity on one end of a body and of − electricity on the other; if the analogy of heat be any guide, we should expect a higher potential where there is much electricity. It must be remembered that there is no such action as induction in heat*, so it is best to disregard analogies and make experiments.

* However, a body may be at the same temperature throughout, but if it be not homogeneous (e. g. if it be partly of glass and partly of water) since the

EXPERIMENT 100. **Potential throughout a body under Induction.** Take the insulated sausage-shaped conductor of Experiments 89 or 94, or any other insulated conductor, and bring near

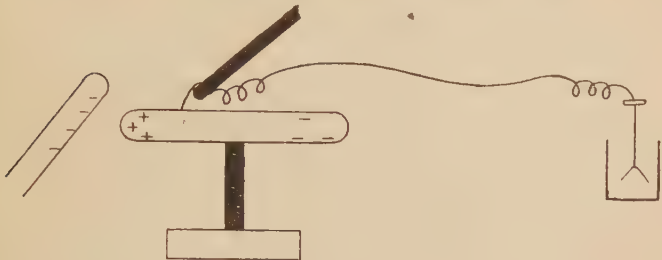


Fig. 157.

to one end a charged body, so that charges may be induced on the insulated conductor. While carefully keeping the inducing body in its position, explore the insulated conductor with the wire from an electroscope in order to determine whether the potential of the body differs in different parts.

The experiment should be repeated, starting with an insulated conductor possessing a charge of its own; and it would be satisfactory to find out whether the potential in the *inside* of a hollow conductor under induction is the same as that of the outside.

In carrying out this experiment an error is very likely to arise owing to the action of the charged body on the wire connecting the electroscope to the body under induction; this occurs especially when the part nearest to the inducing body is being explored. Great care must be exercised to keep the connecting wire close to the body being tested, and as far as possible from the inducing body.

We may deduce from our experiments the law that under all circumstances *the potential of a conductor is the same at all points throughout it.*

276*. It will be seen later that we should make the proviso that the conductor consist of one material throughout; if, for example, it is partly brass and partly iron there may be a difference of potential. This difference is much too small to be perceived by the method of Experiment 100, and it is quite possible that

specific heats of the different parts are not the same, the *total quantity of heat* in different parts is different. But this is not analogous to induction.

the observed difference of potential between the brass and the iron really occurs at their surfaces exposed to air, not to one another. We must also exclude the case of a conductor in which electricity is in motion, as in the voltaic currents dealt with in Part II, in which there is always a difference of potential between points along a wire carrying a current (see p. 102).

277. Potential at points situated between bodies at different potentials. We now come to an application of the idea of potential in which the analogy of temperature ceases to help us. Hitherto we have dealt with the potentials of bodies, and except for electrical induction, the temperature and the potential of a body depend in much the same way on the quantity of heat and of electricity given to it. Now we must pass on to consider what takes place in the space between charged bodies, and extend our notion of potential to include the 'potential at a point' where there is no body which can have a charge, or which can be connected to an electroscope. There will, of course, generally be air between the bodies, and, as a matter of fact, this *can* be charged with electricity in various ways, but we will imagine for the present that the charged bodies are situated in a vacuum, or that if there is a dielectric between them, it has no charge itself.

We will first try to find out something of the manner in which the potential of an uncharged conductor can be altered without transferring any electricity to it, but merely by moving it about in the neighbourhood of a body at a high potential.

EXPERIMENT 101. **Potential of a body in virtue of its position near charged bodies.** Use one of the insulated door-knobs of Experiment 93, and connect it to the electroscope by a long wire. As the body to be kept at a high potential, it will be most convenient to employ a sheet of metal, such as zinc or 'tin,' about 25 × 50 cms., bent at right angles across the middle, so that one half forms the base and one stands upright. To the lower side of the base are fixed three lumps of sealing-wax to act as insulating feet, or the whole may be supported by a slab of paraffin, and it is convenient to have a handle of wax or ebonite stuck on the top of the base, by which it may be moved while charged, as is shown in Fig. 158 *.

Two of these will be needed, placed as in Fig. 158, so that their

* This useful and simple form of what is generally a complicated or unsatisfactory piece of apparatus was designed at Owens College, Manchester; it will be used again in Chapter VII.

upright sides are parallel and about 25 cms. apart. One (A) is charged to a high potential by an electrophorus, the other is earthed or connected direct to the cage of the electroscope.

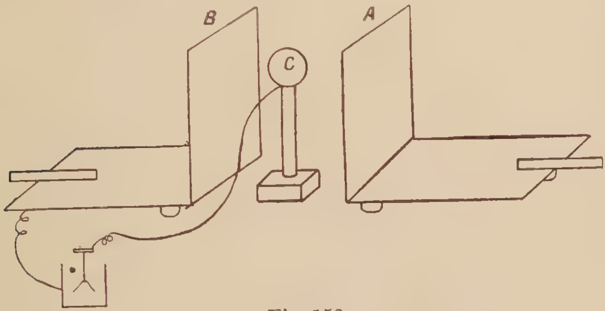


Fig. 158.

The insulated knob C is now connected to the knob of the electroscope, and introduced into the space between A and B. Let it first touch B, and of course the gold-leaves will not separate, since leaves and cage are connected together and therefore at the same potential.

Now, by means of the stand, move C slowly from B towards A. You will probably perceive a gradually increasing divergence of the leaves. If the potential of A is not too high for safety, you can bring C into contact with A, when C and A will have the same potential (Experiment 98).

278. We learn that an insulated uncharged body acquires a gradually increasing potential as it is carried from the earth, or any body at zero potential, towards a body at a + potential (of course this will be a *numerically* increasing − potential if the body be at a − potential). This suggests that it will be convenient to look on every point of the space between the charged body and the earth as having a potential, which is the potential which a small uncharged sphere *would have* if there were one there. This is an extension of our definition of potential, because there is really no electricity at the point to flow to the earth, nor can it be tested by an electroscope, since such an electroscope must be very small compared with the sphere, which itself, by our definition, must be very small indeed. However, the idea of 'potential at a point,' as well as of 'potential of a body,' is very

valuable; and a correct definition which embraces both, following out the mechanical conception of potential, will be given on p. 266.

It will be seen that the analogy with temperature breaks down entirely at this stage; there is no gradual drop of temperature from a hot body through a vacuum to the nearest piece of ice.

279. It may be asked how the potential changes from point to point between the bodies; does its value drop uniformly from that of the highly charged body as you go across to the earth-connected body? In the arrangement of Experiment 101 it does so approximately, but this is far from being the case with the vast majority of bodies. If the charged body is a sphere situated at the centre of a larger conducting sphere connected with the earth, the potential at any point between the spheres can be calculated fairly easily, but it is not proportional to the distance from either sphere, and for arrangements of charged bodies of irregular shapes the calculation of the potential at intermediate points is beyond the power of mathematics.

We are not, however, interested so much in *how* the potential drops in going from one body to another, as in the fact that there is a *gradual* change throughout the intervening space, whether vacuous or occupied by a dielectric.

280. Diagrammatic representation of potential. For the purpose of representing on a diagram the potentials at various points of the space occupied by a number of charged conductors, it will be allowable to assume that the potential falls uniformly from one body to another.

Suppose we have to represent the potential throughout the space

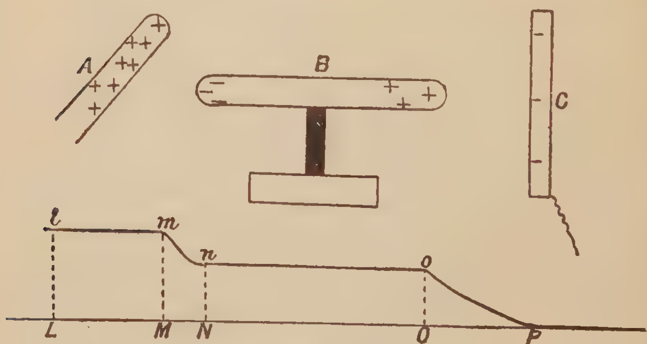


Fig. 159.

occupied by the apparatus in Fig. 159, we can do it as shown in the lower part of the diagram.

Here A is a conductor charged with + electricity, B an uncharged insulated conductor, and C an earthed conductor. In the diagram the line $LMNOP$ is taken as the zero of potential, and lines (such as $L\,l$), drawn above it to represent +, and below it to represent − potential, of lengths proportional to the potential at the corresponding point of the apparatus. The thick line $lmnoP$ then represents the potential at all points of and between A, B, and C.

281. Temperature and Potential.

Temperature	Potential
Temperature is the condition of a body in virtue of which heat tends to pass from it to other bodies, or vice versa.	Potential is the condition of a body in virtue of which electricity tends to pass from it to the earth or vice versa.
Two fixed points of temperature are taken, those of melting ice and boiling water.	One fixed point of potential is taken as zero, that of the earth.
The intermediate range of temperature is subdivided into 100 parts in an arbitrary manner.	The magnitude of the unit of potential is fixed solely by mechanical considerations.
Successive additions of heat generally raise the temperature of a body.	Successive additions of + electricity raise the potential of a body.
Two bodies at different temperatures acquire an intermediate temperature when thermally connected.	Two bodies at different potentials acquire an intermediate potential when electrically connected.
The temperature becomes uniform throughout a body.	The potential is uniform throughout a body.
Heat is uniformly distributed throughout a homogeneous conductor at one temperature.	There may be more electricity at one part than at another, of a body at the same potential throughout.
There is no 'temperature at a point' in space.	The potential at points in space between two bodies at different potentials changes from point to point.

CHAPTER V

Distribution of Electricity on a Conductor

282. We will now investigate the manner in which a charge of electricity distributes itself throughout a conductor, both when left to itself and when under the inductive influence of neighbouring charges. It is obviously impossible to find any connection between the shape and position of a *non-conductor* and the distribution of a charge on it, since the latter by hypothesis stays where it is put, and induction acts *through* a non-conductor without producing a separation of + and − electricity to different parts of the body.

For this investigation we must be provided with a means of testing the *quantity of electricity* on any particular small element of the surface of the conductor. We are met at the outset by a difficulty, since we have not hitherto defined what we mean by a unit quantity of electricity; but we are not as yet concerned with absolute measurements. It will be sufficient for our present purpose to agree that an insulated conductor carries a large charge when it is capable of causing a wide divergence in the leaves of an uncharged electroscope whose knob it is made to touch. We must also agree that the charges successively brought up by such a conductor (using always the same one) can be compared by the divergence they cause in some one electroscope, provided it is uncharged before each test.

283. As an insulated conductor we will use a small piece of sheet metal on an ebonite handle (Fig. 160). We can then, by laying the metal on various parts of the conductor, practically carry away a sample of the surface of the conductor at that point, with any charge it may possess. Such an instrument is called a **Proof-plane.**

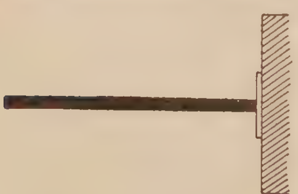


Fig. 160. Proof Plane.

Experiment 102. Charge highly a large insulated body of irregular shape, such as a couple of tins in contact on a block of paraffin. Apply the proof-plane to various parts of the charged body, and test the quantity of electricity carried away each time by means of an electroscope, *carefully discharging it between each test.*

You will probably find that some parts are more highly charged

than others, although, as we have seen (p. 217), they are all at the same potential, since they all form part of one conductor.

Now take regular bodies, and test the distribution of charge on them. First take an insulated sphere, which should not be less than 3 inches in diameter. The proof-plane will not fit accurately on a curved surface, but this error will not be serious if the sphere be large, or the proof-plane small; if the proof-plane is small, the charge it carries off will also be small, and this will need a small electroscope to make it visible.

Fig. 161.

You will probably find that the charge is uniformly distributed over the sphere, provided that it is not near any other conductor or charged body. We may conveniently represent this state of things as in Fig. 161, in which the distance of the dotted line from the surface of the conductor is assumed to represent what we may call the **surface density** of the electricity.

Similarly test the distribution on an insulated cone-shaped conductor with rounded ends, and on a flat circular plate; represent it by dotted lines as in Fig. 161.

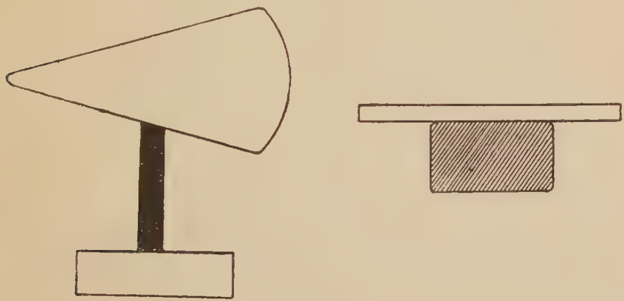


Fig. 162.

Note how electricity seems to accumulate near edges and points, under the influence of the repulsion of one portion of the charge on another.

284. It may appear anomalous that electricity should be crowded together at any point because of its repulsion for the remainder, since

a uniform distribution would appear best calculated to allow each element to avoid its neighbour as much as possible. It must be remembered, however, that it is not only the neighbouring electricity that acts on an element of the charge, but the whole of the charge (although the portion at a greater distance has a less effect, see p. 193). Therefore if there is an outlying part of the conductor, the repulsion of the main charge, spread comparatively thinly over the bulk of the conductor, will cause a certain concentration of electricity on the more distant part (just as a suburb may be crowded compared with the City of London, because the latter is at the centre of a huge urban population and so is undesirable as a place of residence).

285. A more serious difficulty is likely to present itself to the student, in the use of an electroscope to prove that the potential is constant throughout the body, and of the same electroscope to demonstrate the variation in the surface density over the same body. It should be remembered that the divergence of the leaves of an electroscope only indicates how much electricity flows into the leaves from the body being tested. When the electroscope is connected by a wire to different parts of the conductor, the same quantity flows into the leaves from any part, showing that the tendency of the electricity to pass away from that part (i. e. its *potential*) is the same for all. If however, a small part of the surface with its charge is carried away, as by a proof-plane, from the influence of the rest of the charge on the conductor, then the amount of the electricity that will pass to the leaves from the proof-plane depends only on the *charge* carried away on the proof-plane, and not at all on the potential it formerly possessed as part of the surface of the conductor.

Experiment 103. Test the distribution of electricity over an elongated conductor under induction, as shown in Fig. 159; in each case after you have given the electroscope a charge, you must in addition to noting the amount of divergence, find out the *sign* of the charge on the leaves by bringing up a body charged with electricity of a known sign.

Represent the distribution of electricity on the surface as before, by dotted lines.

286. Comparing Experiments 100 and 103, we see that when an insulated conductor is near a charged body, its potential is uniform throughout it, but that there are different quantities of electricity of opposite kinds at various parts of the surface.

The second of these two results might have been foreseen from the first with the help of what we have learnt as to potential. Suppose a + charged body *A* to be situated at a distance from other conductors. By Experiment 101 we know that throughout the space around it, there is a steadily decreasing potential. Now suppose an insulated conducting body *B C D* to be introduced as in Fig. 163. By Experiment 100 the potential at *B* must *now* be the same as at *D*, and both must be the same as at *C*; this could be effected by the potential at *B* being depressed and that at *D* raised; this would occur if a − charge were put at *B* and a + charge at *D*, which would modify the potential at those points due to the charged body *A*.

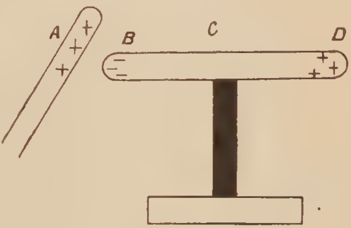


Fig. 163.

Suppose now that *B C D* is earthed; in other words, it has to be brought to zero potential throughout, instead of to the average potential of the space previously occupied by *B C D* (which we have considered as the potential at *C*). There is now no need for a + charge at *D*, but *B* has to be brought to a lower potential than before, so the induced 'bound' charge at *B* is *increased* on earthing *B C D*.

Experiment 104. **No charge on the interior of a conductor.** Charge an insulated hollow conductor, such as an empty tin (Fig. 164). Test whether there is any charge on its inner surface by using a proof-plane (*B*), testing the surface at several points, including one near the edge.

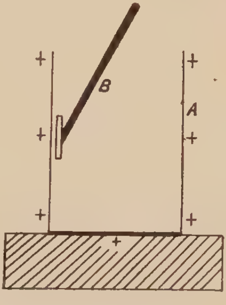


Fig. 164.

You must, of course, withdraw the proof-plane carefully, so that it does not touch the edge in coming out, or it may bring a charge from the edge or give one to it.

Even if the conductor (*A*) be a cylinder of wire-gauze, no charge will be found on the interior; this should be verified, and of course in each case a 'control experiment' should be made to test the

sensitiveness of the electroscope, &c., by taking a sample charge from the outside of *A* to the electroscope.

287. The importance of this fact has led experimenters to devise many methods of testing its truth; among others we may notice Faraday's butterfly-net (Fig. 165). He fixed in an insulated stand (*A*) a net or cone-shaped bag of fine linen (*D*), to the tip of which he had tied two silk threads *B* and *C*, by which he could turn the net inside out without earthing it. He charged the net, and by means of a proof-plane proved the existence of a charge on the outer, and the non-existence of a charge on the inner, surface. Turning the net inside out, he again tested, and found that the charge had passed over to the *new* outer surface.

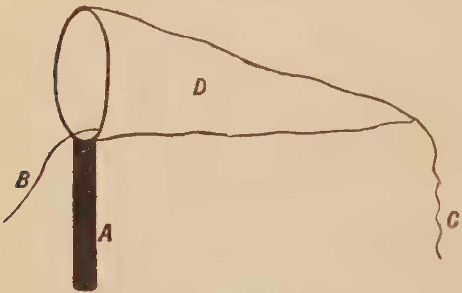


Fig. 165.

Biot's sphere was invented for the same purpose; the student can easily repeat Biot's experiment.

EXPERIMENT 105. Hang up a metal sphere (*A*, Fig. 166) by a piece of dry white silk and electrify it strongly. A pair of hemispherical metal cups (*B*, *C*) must be provided, which exactly fit the sphere, and these must each have an insulating handle.

Holding them by these handles, fit the hemispheres on the sphere, then pull them apart in such a way that neither touches the sphere at any point after they have begun to leave it.

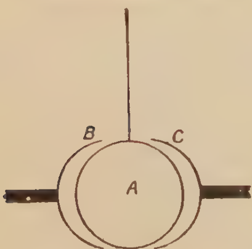


Fig. 166.

Now test each hemisphere and the original sphere for electricity; it will all be found on the hemispheres, if the experiment has been carefully carried out.

288. We can now see the reason why we can use, for experiments in electrostatics, an insulator whose surface has been made to conduct

by means of a layer of tin-foil or even of black lead, instead of a solid metal conductor, since even in the latter case all the charge would be on the surface. When electricity is in motion, however, it does not confine itself to the surface; hence solid wires are used to convey electric currents *.

EXPERIMENT 106. **Charge induced on inner surface of a conductor by a free charge of electricity.** Take an insulated hollow conductor, such as a tin can on a stand (*A*, Fig. 167), and charge it; by Experiment 104 we know that there is no charge on the inner surface.

Now lower into it a large charged body, such as a brass ball (*B*) hung by silk, and test the inner surface by a proof-plane (*C*). If a charge be found, determine whether it is of the same sign as that on *B*.

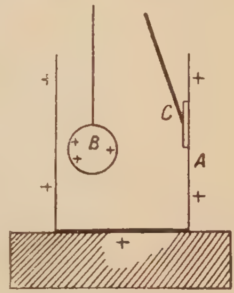


Fig. 167.

289. We must then modify the law, suggested by Experiments 104 and 105, as follows: *There is no charge in the interior of a conductor unless there is inside the conductor a charged body insulated from it*

290. We are now in a position to understand completely the following experiment, first made by Faraday with an insulated pewter ice-pail (a vessel about eleven inches high and seven inches diameter).

EXPERIMENT 107. **Faraday's Ice-pail experiment.** Insulate a deep can (*A*, Fig. 168) and connect it by a wire with a distant gold-leaf electroscope (*B*), whose cage is earthed. Provide yourself with a large round metal ball (*C*), suspended by a long piece of dry white silk †. Discharge *A*, charge *C* with, say, + electricity. Lower *C* into *A*; notice that as *C* approaches *A*, and until it is thoroughly within the mouth of *A*, the divergence of *B* increases; but that once it is within *A*, no movement of *C* affects the divergence of the

* In the case of currents which very rapidly change their direction, such as occur when a lightning-conductor is struck and carries a discharge to the earth, the majority of the current is situated in the surface-layers of the conductor; hence lightning-conductors are often made of flat strips of metal or of a number of thin wires twisted together.

† The silk must be long in order to guard against an inductive effect of the hand.

leaves of the electroscope. Test the sign of the electricity on the electroscope by bringing towards its knob a body carrying electricity of known sign.

Now slowly withdraw the ball (*C*) without letting it touch the can. Note whether the leaves completely collapse.

It is clear from Experiment 106 that a – charge is induced on the

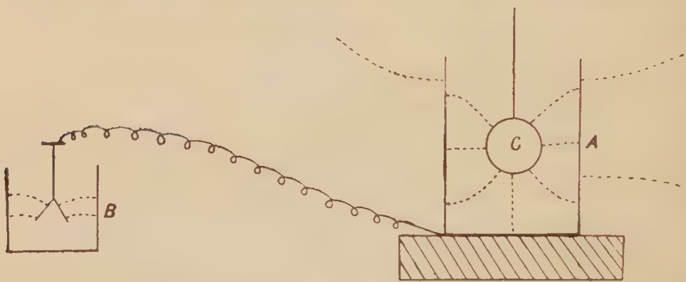


Fig. 168.

inside surface of the can, and from Experiment 107 that a + charge is driven to the electroscope; part of the latter, however, probably remains on the outer surface of the can, since it is a free charge and will distribute itself over the whole surface of the conductor.

Experiment 108. Introduce a charged ball exactly as in Experiment 107, but now, when it is completely within the can, make it touch the inner surface, carefully watching the electroscope the while.

Now withdraw the ball and see whether the leaves collapse at all. Test the ball to find out if it carries away a charge.

Since the induced – charge exactly neutralizes the + charge originally on the ball, it must be equal to it in quantity; thus we see that the *total quantity of electricity induced by a charge is equal to the inducing charge.* Note that if the inducing charge is not entirely surrounded by a conductor, the charge induced on that conductor is not so great as the inducing charge, since some electricity is induced on the walls of the room, &c. Note also that the only way in which we can make one conductor give up its whole charge to another is to put the first wholly inside the second, and then put them into contact; if they touch with their outer surfaces, the charge is merely shared between them.

Experiment 109. Run some melted paraffin wax into the

bottom of an 'ice-pail' (A, Fig. 169), connected as in Experiment 107 to an electroscope, and, when the wax is set, put into the ice-pail a smaller can (B) provided with an insulating handle (C). The wax will insulate one can from the other.

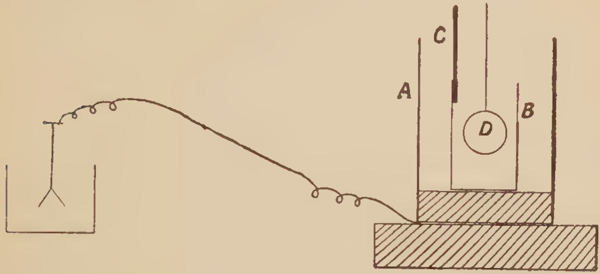


Fig. 169.

Into the inner can lower a positively charged ball (D) and note the divergence of the leaves. We know that there must be a − charge inside B, and a + charge outside it; this latter induces a − charge on the inner surface of A, and repels a + charge to the outside of A and to the electroscope.

Now by means of the handle C bring B into contact with A, taking care that the ball D is not touched. The electroscope should not be affected, since the charges on the inside of A and the outside of B, which were bound together, have now destroyed each other.

Now remove the ball D. Note and explain the effect on the electroscope.

Next remove the can B by the insulating handle. Note the effect on the electroscope. Test the ball D and the can B.

291. We have here a method of charging the can A (we can, of course, dispense with the electroscope) with a charge exactly equal, in amount and sign, to that on a body D, without affecting that charge. If the whole operation be repeated, after discharging the inner can B while it is removed from A, we can add another equal charge to A; so that *we can charge a body with any desired multiple of a given charge.*

292. By the use of a single insulated can and an electroscope we

have proved the equality of an inducing and induced charge; we can also prove, more satisfactorily than by Experiment 87, that the charges produced by the friction of two bodies are equal and opposite. The bodies must be mounted on insulating handles, and rubbed together inside the can. The electroscope will not be affected until one or other of the bodies rubbed is removed, although these bodies are separated; and the sign of the electricity repelled to the electroscope will depend on which of the two bodies is removed.

293. No electric force inside a conductor. If we assume the truth of the law that has been suggested by Experiments 104 and 105, that there is no charge on the interior surface of a hollow conductor, it follows that there can be no lines of force passing through the medium inside the hollow conductor, since such lines of force merely connect + and − charges.

Now a line of force is a way of expressing the tendency of a charge on one part of a conductor to get to a charge on another conductor, through the dielectric that separates the charges. The fact, then, that there are no lines of force proves that there is no tendency of the charges on the conductor to pass through the dielectric within it, i. e. that *the potential is the same throughout the conducting body, including any dielectric enveloped by the body.*

Thus Experiments 99 and 100 and Experiments 104 and 105 are merely different ways of proving the same thing.

294. The absence of lines of force inside a conductor is of such great importance that we will give further experimental verification, using the most delicate instrument available.

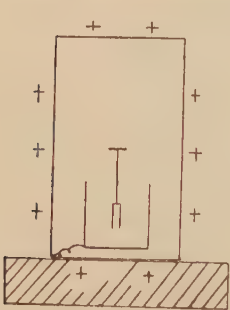


Fig. 170.

EXPERIMENT 110. Get a cylinder of wire-gauze large enough to contain a gold-leaf electroscope; or a tin cylinder with a small window in one side through which the electroscope can be observed. Put the cylinder on an insulating stand so as to surround the electroscope, and cover both top and bottom of the cylinder with a conductor (Fig. 170).

The knob of the electroscope may be left unconnected or connected to any point of the cylinder, and if

the electroscope is provided with a cage, this cage may be connected to any other part of the cylinder.

Electrify the cylinder as highly as possible, and induce electricity in it by bringing near to it a charged body, and try to detect any movement of the leaves of the electroscope.

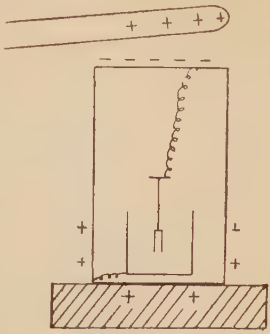


Fig. 171.

295. Faraday carried out this experiment very completely. He had a small room built, twelve feet each way, made of wood framing covered with paper, with wires stretched along the walls in all directions. This was insulated; he then got into it and it was charged until sparks were flying from its outer surface. He could perceive within the room no sign of electrification, or electric force capable of separating the electricities on an uncharged body, even by his most sensitive pieces of apparatus.

Notice that in all this we have assumed that there is no charge, on a body insulated from the hollow conductor, present inside the conductor, as there was in Experiment 106, for lines of force will then run from this charge to the electricity which it induces on the inner surface of the conductor.

296. If we have an electroscope provided with a cage which practically entirely surrounds the leaves, we can conveniently carry out Experiment 110, and others.

Experiment 111. Stand a gold-leaf electroscope, provided with a cage, on an insulating stand. Connect the knob with the cage by a wire. Electrify the whole as highly as possible. The absence of effect should show that there is no electric force within it.

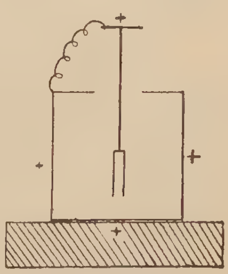


Fig. 172.

Discharge the electroscope and disconnect the knob from the cage (leaving it still on its insulating stand). Give a small charge to the knob by means of a charged proof-plane, so as to raise the potential of the leaves above that of

the cage. Now supply to the cage a series of charges of the same sign, and watch the gradual collapse of the leaves as the potential of the cage rises to that of the leaves. When they are the same, earth the knob; this makes the potential of the leaves again different from that of the cage, so the leaves should diverge again.

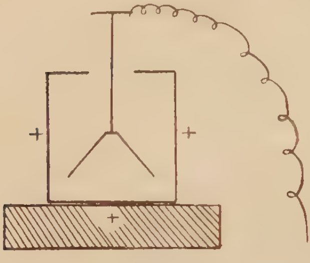


Fig. 173.

This illustrates the necessity of earthing the cage of an electroscope, when it is used to measure potentials; in this case we have zero potential of the knob indicated by a divergence, because the cage is not at zero potential. As a matter of fact, the electroscope always indicates *difference* of potential between its leaves and cage.

CHAPTER VI

Electric Machines

297. Action of points. When electricity has been produced by friction on a non-conductor, as on an ebonite ruler, we have hitherto been unable to collect it on a conductor, and consequently it has been unavailable; we have only been able to use it, as in the electrophorus, to produce an available charge by induction. The early experimenters did not know of this property of 'induction,' and wished to charge their conductors from rubbed insulators; they discovered that they could do so by the help of sharp metal points. The behaviour of such points when near electrified bodies we will now study.

298. We found in Experiment 102 that if a charged conductor is somewhat pointed, the electricity accumulates near the point in greater quantity than in the flatter parts; if the point is sharp the excess becomes enormously greater. Now when the surface density of electricity (see p. 225) rises above a certain value at any point (about 8 units per sq. cm., if the body is surrounded with air), the air itself near that point acquires a charge, and being similarly charged

is repelled from the body; so that the body loses its charge until the surface density sinks to a possible value.

If, then, we have a needle-point connected to a charged body, nearly the whole of the charge will accumulate on the point and will probably discharge itself into the air. Hence no sharp points are permissible in any body expected to keep a charge; all corners and edges must be rounded, and all wires should end in knobs.

EXPERIMENT 112. Insulate a conductor (*A*, Fig. 174) and lay a sewing-needle (*B*) on it so that its point projects. Charge *A* as highly as you can with an electrophorus; test the charge at some point of *A* by means of a proof-plane. Hold your finger about an inch in front of the needle-point for a minute or two, testing the charge at intervals, until no further change occurs. Note whether *A* loses any charge, and if so whether it loses it all.

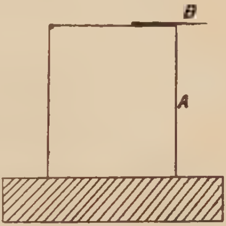


Fig. 174.

Now stick a pith-ball, or a round bit of cork, &c., on the point of the needle and repeat the experiment.

299. Such a method of discharging conductors is not of much use, except as showing us what we must avoid, and in its present form is not applicable to the discharge of a non-conductor. For this purpose we must employ induction.

EXPERIMENT 113. Charge the electrophorus cover as highly as possible and fix it up by its insulating handle. Test its charge by means of a small proof-plane and electroscope.

Hold a needle in your hand with its point towards and about half an inch from the electrophorus cover, for about half a minute. Again test the charge of the cover.

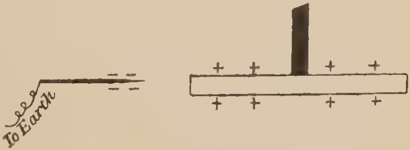


Fig. 175.

Since the needle is earthed by your hand it will have a − charge induced on its point, and, as explained in Article 298, this should cause a stream of negatively charged air to flow from it to the electrophorus cover. This air neutralizes the + charge there until it gets too weak

to induce enough electricity on the needle to cause a discharge. The existence of this stream of air will be demonstrated (p. 258).

300. The same process will obviously serve to discharge a non-conductor (partially); and if the needle is insulated, or connected to an insulated conductor instead of to the earth, then the + free charge produced by the induction will be left on the conductor, so that the charge will be practically transferred from the non-conductor to the conductor, by *convection* through the air.

EXPERIMENT 114. **Use of a needle in collecting the charge from a non-conductor.** Arrange a needle (B, Fig. 176) on the top of an insulated uncharged tin (A), as in Experiment 112. Excite strongly the ebonite disk (C) of an electrophorus, and bring it near the point of B. Move C in front of, and about half an inch from, the needle-point, so that most of the surface of C passes near it. Remove C and quickly take a sample of the charge on A by means of a proof-plane (if you waste time the needle may discharge A). Test the sample for quantity and sign by means of an electroscope; if the quantity is insufficient repeat with the freshly rubbed ebonite disk as often as is necessary. Also test C by an electroscope to find if it has lost its charge, wholly or in part.

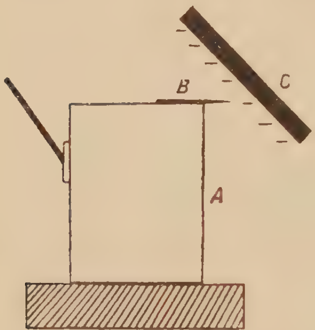


Fig. 176.

The student must carefully distinguish between this and the inductive effect of the charge on C. The latter would cease when C was withdrawn, and the charge on C would not be affected. In this case electricity actually passes through the air (by *convection*), so that the air does not act as a dielectric.

301. Frictional machines. A glass plate or a glass cylinder, such as a bottle, is mounted on an axle so that it may be turned round by a handle, and a pad of silk is made to press against it at one part, so that as the glass passes away from the silk it carries with it a + charge. This is collected by a row of sharp points a little further on, and conducted to a large insulated conductor called the 'prime conductor.' The glass passes on partly discharged and again is

rubbed by the silk, so that there is a continuous production and collection of + electricity.

If the rubber is insulated and connected to another prime conductor, − electricity may be drawn from this.

302. Whenever glass has to be rubbed by silk, it is found that more electricity will be produced if the silk is covered with a layer of metallic powder, stuck to it by stiff grease; the best preparation is an *amalgam* of equal parts of tin and zinc mixed while melted with twice their weight of mercury. This amalgam is generally spread over the rubbers used to electrify glass rods as in Experiment 84, and as it is the metal that touches the glass, leather may be substituted for silk.

303. In Fig. 177, *A* is the glass cylinder, turned by a handle; *B* is the silk or leather rubber mounted on an insulating support *C*, and

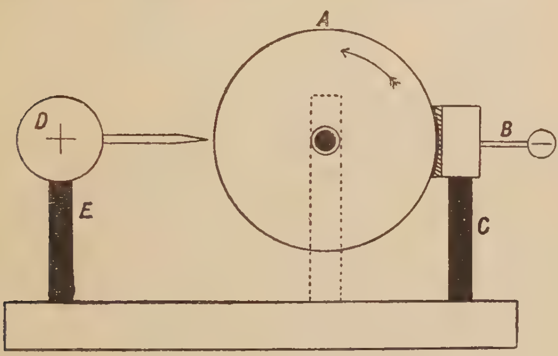


Fig. 177. Frictional Machine.

furnished with a brass knob in electrical connection with the amalgam on the rubber, so that − electricity can be drawn from it; *D* is the prime conductor mounted on the insulating support *E*, and furnished with a row of sharp points facing and close to the glass cylinder.

The cylinder is turned 'counter-clockwise,' and the rubber is firmly pressed against it. In order to prevent the loss of charge from the excited surface of the cylinder between *B* and *E*, a flap of silk is often attached to *B* and rests on the surface of the glass, so that particles of dust will not disperse the charge.

This and the plate-machine are of no practical importance now

that much more efficient machines are available*; they have no theoretical interest, and will not be considered further.

Induction Machines

304. Voss's machine. The machine usually known by this name is the result of the inventions of a series of men, Nicholson, Holtz, Toepler, and Voss, in their efforts to make an electrophorus more easy to use and more efficient. One important principle is added to that of the electrophorus, that of 'reciprocal accumulation'; otherwise it differs from an electrophorus only in its mechanical arrangements.

The principle can best be explained with the help of a diagram, which, for clearness of drawing, represents a cross-section of two concentric glass cylinders (A and B, Fig. 178), the outer of which is fixed, the inner movable round its centre.

A is a fixed glass cylinder, to the outside surface of which are pasted two sheets of tin-foil, C and C', which we will call *armatures*. B is a glass cylinder which rotates clockwise, and carries on its inner surface a number of metal plates or studs; any number of these may be used, but we will assume that there are six, α, β, γ, δ, ϵ, ζ, and we will call them *carriers*.

D and D' are a pair of *collecting brushes* to collect the electricity and carry it to prime conductors; these consist either of a row of sharp points, or a brush of flexible wires, or both.

E and E' are *neutralizing brushes*, consisting of flexible wire brushes carried on and connected together by a metal rod, which may be, but is not necessarily or usually, earthed.

G and G' are *appropriating brushes*, which are fixed to the armatures C and C' and reach over the end of the cylinders, so that they touch the carriers as the latter pass.

First, let us imagine that α possesses a small + charge as it leaves E'; this may be acquired by friction with E'. It will, on touching the appropriating brush G, give up a large proportion of this + charge, which will spread over the armature C, and the remainder it will carry on to the position γ, where it will surrender its charge (or most of it) to the collecting brush D.

The carrier will pass on uncharged to the position δ. Here it will act the part of the 'cover' of an electrophorus, the armature C with

* Frictional machines are hard to turn, and only work well under the most favourable weather conditions.

its + charge acting as the 'disk,' and the neutralizing brush E as the finger. It will here acquire by induction a – charge, which it will carry away. On touching G' it will give up most of this – charge to that appropriating brush, and the armature C' will thus acquire a – charge. The remnant of the – charge on the carrier will be collected by D', being helped to leave ζ by the repulsion of the similar charge on the armature behind it.

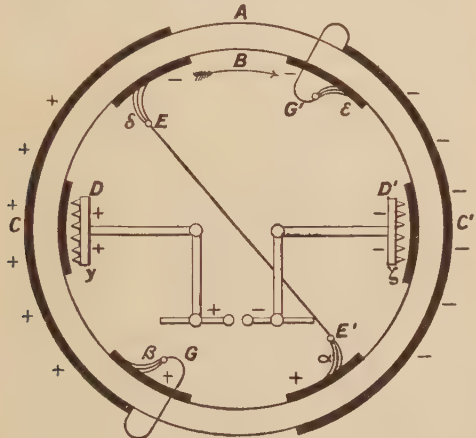


Fig. 178. Voss Machine.

The carrier will then pass on uncharged until it touches E' again, when it again acts the part of the cover of an electrophorus, but this time the disk has a – charge, so that the carrier will carry away a + charge.

Here begins the 'reciprocal accumulation,' because this + charge increases the charge on C, so that the – charge induced on the carrier in the position δ is increased. Hence the next contribution to the appropriating brush G' is larger than before, which in its turn increases the induction in the position α; and so on.

As each carrier is going through this cycle of operations, the armatures very quickly become highly charged, so that the appropriating brushes no longer take toll of the carriers as they pass the positions β and ϵ, except to supply slight losses to the air, &c. The carriers will then reach the collecting brushes D and D' with undiminished charges, which they will surrender, so that a large supply of + and – electricity will appear on the prime conductors.

305. Practical form of Voss machine. The form of Voss, or Toepler-Holtz, machine usually adopted is as follows.

A large circular glass plate is fixed upright, and carries on its *back* two armatures of tin-foil covered with paper and two appropriating brushes reaching over to the face of the disk. Another circular glass plate is mounted on a horizontal axis so as to revolve parallel to and close in front of the former plate. This has the 'carriers' pasted on its front surface. The neutralizing brushes are carried on a rod passing diagonally in front of this plate, and collecting brushes are mounted also in front of the movable plate. These latter brushes are usually connected each to the inner coating of a Leyden jar (see p. 250) which acts as the prime conductor.

EXPERIMENT 115. Examine a Voss machine and identify its various parts. Separate the knobs connected to the collecting brushes, if, as is usually the case, they can be adjusted to stand at various distances apart. Then turn the machine *the right way round* until an increased resistance is felt, or a hissing sound is heard. Then by means of the ebonite handles gradually approach the knobs to each other until sparks pass between them.

While keeping the machine charged by gently turning it, the knobs being placed too far apart to allow a spark to pass, test (by a proof-plane and an electroscope charged with electricity of a known sign) the sign of the charges on the armatures and the discharging knobs, and on the carriers in their various positions, verifying (or not) Fig. 178.

It is possible that the machine will not 'excite' without assistance, though this is rare. If so, charge one of the armatures, or hold behind it, opposite to one of the neutralizing brushes, a rubbed stick of ebonite or sealing-wax. As seen above, the least charge will rapidly mount up if the machine is working properly.

306. Wimshurst machine. This is a double-acting Voss machine; it is represented diagrammatically in Fig. 179. Each cylinder turns, but in opposite directions; suppose A turns counter-clockwise and B clockwise. There are carriers on *both* cylinders, but no fixed armatures or appropriating brushes. The collecting brushes and combs collect from the carriers on both cylinders simultaneously; there are two neutralizing rods (E and E_1) set at right angles to one another. Let us first trace the career of a carrier on the inner

cylinder *B*. At α we will assume it acquires in some way a + charge *.

It carries this + charge to β, where it induces a - charge on β_1, which is at that moment earthed by E_1. It passes on and surrenders its charge to the collecting brush *D*, and passes on practically uncharged.

Fig. 179. Wimshurst Machine.

Now let us follow the outside carrier which acquired a - charge at β_1; this at the point α_1 acts inductively on the carrier, which has then reached α, and gives it a + charge, itself passing on and giving its - charge to the collector *D'*. By this process + charges are being continually induced on the inner carriers at α, which in their turn produce - charges as they pass the outer carriers at β_1, so that the opposite electricities are being continually conveyed to the two collectors.

Now consider the action of the neutralizing rod E_1. It is usually *not* earthed, so that the - charge driven away from α by induction is repelled to δ. This is carried on to ϵ, where it acts inductively on ϵ_1 and charges it positively. Thus the same process is going on in

* If necessary, by a rubbed rod being held outside α_1 so as to act as the charged disk of an electrophorus, α being the cover and the neutralizing brush acting as the finger.

both halves of the cylinder, and it will be noticed that the right-hand collector receives − electricity from both cylinders, and the left-hand collector receives + electricity.

307. Practical form of Wimshurst. The practical form of the Wimshurst consists of two parallel plates mounted so as to turn freely on a fixed axle. These are driven round in opposite directions by belts from an axle turned by a handle, one of the belts being crossed. A Wimshurst machine should be carefully examined by the student and its different parts identified.

The glass plates, since they are not exposed to friction, are usually coated with varnish to improve the insulation, the sectors or carriers being unvarnished. This varnish surface takes its share of producing the electricity, since the sharp points of the neutralizing brushes and of the collectors serve to charge and discharge even a non-conductor.

308. Since there is no armature with its permanent charge, the Wimshurst machine is liable to reverse the sign of the electricities on the discharging knobs after a spark has passed. This objection can be to some extent overcome in practice by making the discharge pass between balls of very different radii, the larger ball being for the − charge.

It is to be noted with this as with the Voss machine, that if a conductor is to be charged as highly as possible with either kind of electricity, the collector producing the other kind of electricity should be connected to the earth.

309. Induction-machines as dynamo and motor. If the driving-band is taken off a Voss machine so that the movable disk may turn very easily, and if its knobs are then connected by wires to the knobs of a Wimshurst machine in action, the electricity supplied by the Wimshurst will suffice to drive the Voss machine, but in the opposite direction to that which would produce electricity. It will probably be necessary to start the Voss by hand, since otherwise the electricity will not reach the fixed armatures.

The reason is merely that the attraction of the armatures for the carriers produces a movement of the plate; but it is an interesting example of the transformation of energy, the same machine being able to convert mechanical into electrical energy, or vice versa.

CHAPTER VII

CONDENSERS

310. ALTHOUGH we do not as yet need to be able to measure numerically the quantity of electricity on a body, it will be convenient, for the sake of clearness of idea and precision of statement, to fix on a definite quantity as our unit; once we have obtained our unit, we have seen (in Experiment 109) how to multiply it at pleasure. The most suitable property by which to define it is the force it exerts, not on an uncharged body, but on another quantity of electricity. As we must define these quantities both at once, we will take two similar and equal quantities and imagine them collected on extremely small spheres 1 cm. apart; then if these repel one another with *unit force* (the name of which on the C. G. S. system is the **dyne**, its magnitude being roughly the weight of 1 mg.), we will consider them to be each of magnitude 1.

So that our definition of unit quantity of electricity is as follows:—*A unit quantity of electricity is of such magnitude as to repel with a force of one dyne an equal quantity of electricity at a distance of one centimetre; both charges being of the same sign and situated in air.*

EXPERIMENT 116. Take two tin cans, one large and the other small, and stand them on separate insulators. Connect one with an electroscope.

Now charge a metal knob carried on an insulating handle, and lower it into the can connected to the electroscope, and note the potential of the can as shown by the electroscope. Remove the charged ball from the can; disconnect the electroscope from that can and connect it to the other, and then lower the ball into the second can, again noting its potential.

You are using the same quantity of electricity each time, and therefore the *quantity* of electricity repelled on to the outer surface of the can (and the electroscope) must be the same in each case (by Faraday's ice-pail experiment); so that we find that the same charge will raise different bodies to different potentials.

This is exactly analogous to heat, for with bodies of different 'capacities for heat' the same number of calories will produce a different rise of temperature.

311. We must therefore have some such thing as 'capacity for

electricity' belonging to an insulated conductor; a body with a large capacity needing a large charge to raise it to a certain potential, while a body with a small capacity needs a much smaller quantity to bring it up to the same potential.

Definition of the capacity of a body:—

The capacity of a body is the number of units of electricity which are needed to raise its potential from zero to unity.

Compare the definition of the 'capacity for heat' of a body, as being the number of units of heat (calories) needed to raise its temperature by 1° C.

It will be remembered that we have not yet settled on the meaning of 'unit rise of potential,' so the above definition of capacity will not enable us to determine practically the numerical value of the capacity of any body.

312. We found reason, in Experiment 97, to believe that the potential of a body increases with each addition of electricity to it, but we in no way proved that the rise of potential is directly proportional to the additional charges; this can only be proved or disproved when we have fixed on a method of defining 'potential' numerically; we *could* define it in such a way that the rise of potential would be proportional to the square or square root, &c., of the charge. As a matter of fact, potential is so defined that the potential of a body *is* proportional to the charge on it (see p. 268); so we may say that, if Q represents the charge on it, and V the potential to which this charge raises it,

$$V = kQ \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad \text{(A)}$$

where k is some number (or numerical coefficient).

Now we have defined the capacity C of the body as being the number of units required to raise its potential to unity; i. e. $V = 1$ when $Q = C$,

$$\therefore \quad 1 = k \times C,$$

which gives us the value of k,

$$k = \frac{1}{C},$$

and (A) becomes

$$V = \frac{1}{C} \times Q,$$

$$\text{or} \quad \mathbf{Q = C \times V}.$$

In words, *The quantity of electricity on a body is equal to its capacity multiplied by its potential.*

313. The capacity of a body depends on the area of its surface. In the case of heat, the capacity of a body of given material, say brass, depends directly on the *weight* of the body, since the heat permeates the whole mass of the body; in the case of electricity, since it resides entirely on the surface, the *area* of the latter is obviously the important factor.

EXPERIMENT 117. Get or make a kind of 'roller-blind' of tin-foil, rolling on a long thin rod of ebonite. One edge of a rectangular piece of tin-foil about 15 cms. × 10 cms. is pasted along the middle of the rod, so that as the rod is twisted round the tin-foil will roll up round it; keep it tight by clipping a piece of sheet lead to the middle of the bottom edge. At least 5 cms. of ebonite should project at each end.

Between the lead and the tin-foil clip one end of a piece of No. 36 copper wire, the other end of which is attached to a *small* gold-leaf electroscope.

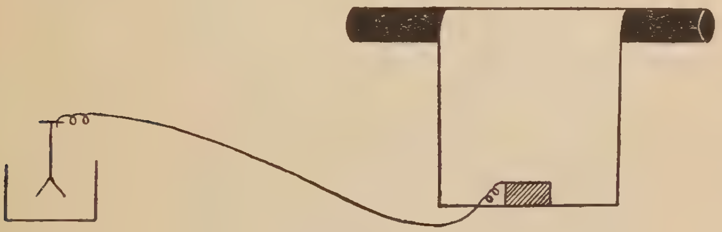


Fig. 180.

Holding the roller by one end, the blind being fully unrolled, charge it to a moderate potential as shown by the electroscope.

Now roll up the blind, of course being careful not to discharge it, and watch the electroscope for indications of an increase or decrease of potential.

If the potential increases, since the charge is constant the capacity must have decreased.

314. The capacity of a body is not proportional to the area of its surface, but depends on its shape as well. For example, it can be shown (p. 268) that the capacity of a sphere far removed from other bodies is simply equal to its radius, whereas its surface area is proportional to the square of the radius.

315. Effect of the neighbourhood of other bodies on the capacity of a body. We now come to an effect to which we have *no* analogy in heat.

EXPERIMENT 118. Take a pair of plates bent at right angles and insulated, such as are described on p. 220. Connect one (which we will

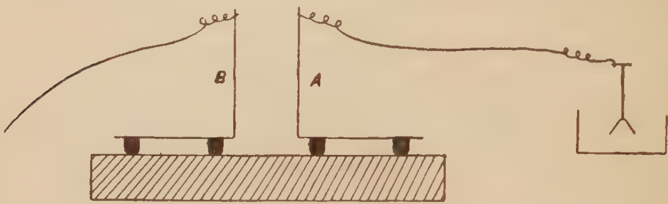


Fig. 181.

call A) to an electroscope, charge it to as high a potential as the electroscope will safely bear, and watch the electroscope to see that the insulation is good; if there is a perceptible leakage, you must put the plate on a slab of paraffin as in the diagram.

Now connect the other plate (call it B) to earth by a wire, and slowly slide it up, keeping it parallel to A. Note any change in the potential of A; if it decreases we see that the capacity of a body is increased by the close proximity of an earth-connected conductor (since the same charge only raises it to a lower potential).

Remove B and note whether A recovers its former potential.

Now, bringing B again close up to A, add more charge to A by means of a metal ball on an insulating handle, until the potential rises to its former value. Since a greater quantity of electricity can be given to A and still produce only the same potential-raising effect as before B was brought up, this electricity is said to be 'condensed' on A, and the pair of plates is called a **condenser.**

Discharge A before removing B, to avoid damage to the electroscope.

316. We may define a condenser as a body whose capacity is artificially raised. We ordinarily speak of the capacity of the condenser; strictly speaking it should be 'the capacity of the body, as increased by the proximity of the earth-connected body.'

EXPERIMENT 119. **Influence of the dielectric on the capacity of a condenser.** Carefully remove any charge there may be on

a slab of paraffin or of ebonite or of warm glass, whichever is most convenient, by passing it through a flame (or by breathing gently on it and wiping it with a finger, the method preferred by Faraday).

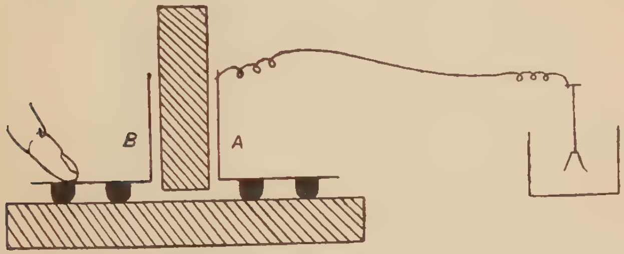


Fig. 182.

Bring the earth-connected plate B (Fig. 182) close enough to A to admit the slab between them without actual contact (this should be avoided, to guard against the production of electricity by the friction). Now with the slab between A and B charge A to a fairly high potential; remove the slab (B being earthed all the time), carefully watching for indications of a change in the potential of A.

Any change will show that induction goes on through the material of the slab either better or worse than through air, for it is clearly the accumulation near to B of the electricity on A as a bound charge that causes the potential of A to drop when B is brought up. If then the inclusion of the slab increases this fall of potential, it is due to the superior *inductive power* of the slab, or vice versa.

Determine whether the material of the slab has a greater or less 'inductive power' than air.

317. Specific inductive capacity. Since the inductive power, or 'inductive capacity' of dielectrics differs, we must provide ourselves with a method of expressing this difference numerically, and it is most simply done by comparing them with a standard substance.

The standard dielectric with which all others are compared is *dry air*, and the comparison is made between the capacities of any condenser (such as a pair of parallel metal plates), having first the given substance, and second, air, as the dielectric. The number so found is

called the **specific** * **inductive capacity** of the material, and it may be defined as 'the number by which it is necessary to multiply the capacity of a condenser having air as its dielectric in order to obtain the capacity of the same condenser with the substance as its dielectric.' The following is the value for a few dielectrics :—

Specific Inductive Capacities (K).

Air	1
Sulphur . . .	3·16 to 4·48
Glass	6·1 to 7·37
Ebonite . . .	3·15
Mica	6·6
Turpentine . . .	2·23
Paraffin (solid) . .	2·29
Petroleum . . .	2·05

318. Franklin's pane. A form of condenser more convenient than the one used in Experiment 118 may be made as follows : a sheet of glass is taken and on each side is pasted a sheet of tin-foil, leaving a margin of at least 5 cms. all round. This uncovered glass should be carefully varnished.

Fig. 183.

EXPERIMENT 120. Lay the Franklin's pane on an insulating stand as in Fig. 183, and by means of an electrophorus cover, or better, by a Voss or Wimshurst machine, charge the upper sheet of tin-foil as highly as you can, counting the number of sparks that pass into the tin-foil. (This gives a *very* rough measure of the capacity of the body, or of the condenser with the unelectrified plate insulated.)

The reason why electricity ceases to pass into the upper sheet is that the tin-foil has reached the same potential as the electrophorus cover or the conductor of the machine.

Now bring your knuckle near to the *lower* plate of the condenser, and see if there is any 'free' electricity there, ready to pass to earth. If so, it shows that the lower plate is at a higher potential

* The word 'specific' always implies a comparison with a standard substance, as in specific gravity, specific heat, &c.

than the earth (from our definition of potential on p. 214), so that raising the potential of the upper plate has raised that of the lower one also. Thus a change in the potential of one plate affects that of the other.

If then we bring down the potential of the lower plate to zero by touching it, we may expect the upper one to have its potential brought down too (though not to zero); and in that case the charged electrophorus cover or conductor of the machine will again be at a higher potential than the upper plate, and so will be capable of transferring electricity to it.

See if this is so.

You can fully charge a condenser in this way, by alternately charging one plate to the potential of the machine, and then lowering the potential somewhat by earthing the other plate. This allows the free electricity to pass to earth, or brings up electricity of opposite sign to that on the first plate, whichever way you choose to regard it; in either case the potential of the second plate is brought to zero, and the same initial charge on the first plate is no longer able to raise its potential so high.

Try this method, counting the total number of sparks passed into the upper plate, and compare with the number which can be passed in when the lower plate is kept permanently connected to earth.

If now one finger be put on the earthed plate and the other be brought to touch the plate charged from the machine, a 'shock' will be felt, which varies in unpleasantness with the size of the tin-foil and of the charging-machine. Try it.

319*. If we revert once more to the idea of bound and free charges, we may get another and perhaps clearer view of the 'condensation' of electricity on Franklin's pane. Suppose that the upper plate, which we will call A, is

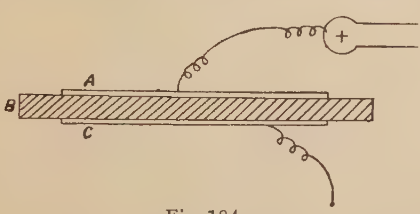


Fig. 184.

connected to the + conductor of a machine, and the lower (C) to the earth; then the inner surface of C (i. e. that next the glass) will be covered with a − charge

drawn from the earth, and this binds a + charge on the inner face of *A*. This latter charge on *A* is in addition to the + charge which would reside on *A* if it were at its actual potential and *C* were absent. Thus the potential of *A* is raised to its actual level, not by the total charge on *A*, but by the small residue which the charge brought from the earth to *C* is incapable of binding; this small residue binds an equal quantity of − electricity on the walls of the room just as though *C* were absent.

320. Leyden jar. A more usual form of condenser for electrostatic work is the 'Leyden jar.'

The invention of this method of 'accumulating' electricity is variously ascribed to Kleist, Bishop of Pomerania, Prof. Muschenbroeck of Leyden, and his pupil Cuneus. Muschenbroeck in 1745 tried to collect electricity in a bottle full of water, passing it in by a wire through the cork while Cuneus held the bottle in one hand. The hand thus took the place of the earthed sheet of tin-foil, the water of the other; and on taking hold of the wire to remove the cork and test the water for electrification, Cuneus received a shock running through his arms and chest.

321. Two forms of Leyden jar are now common: Fig. 185 (i) represents a glass jar *A* having an inner (*B*) and an outer (*C*) coating of tin-foil. The uncovered glass is varnished to improve the insulation. A wooden cover *D* supports a rod *E*, ending in a knob *F* and a chain *G*.

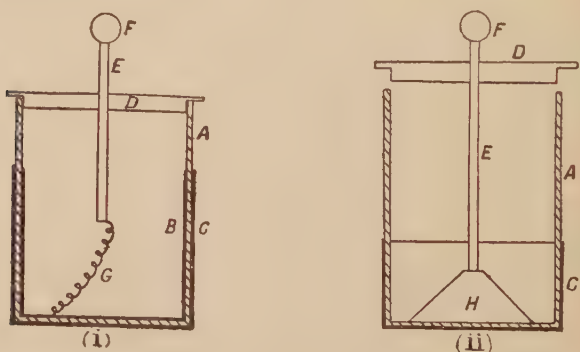


Fig. 185. Leyden Jars.

Fig. 185 (ii) represents a better form invented by Lord Kelvin; here the inner coating is replaced by strong sulphuric acid, which

keeps *A* dry. The rod and knob are supported on a leaden foot standing in the acid, and in use the cover *D* is lifted out of contact with the glass jar.

322. Discharging tongs. In order safely to discharge a Leyden jar (since it would be dangerous to do so through the body in the case of a large jar highly charged) it is usual to employ a pair of metal arms as in Fig. 186, jointed at *A* so as to be set at any angle, carried on an insulating handle *B*.

Fig. 186.

As the insulating handle may sometimes be damp, it is advisable always to touch one of the knobs to the coating of the jar which is earthed, and *then* bring the other near the charged coating; if this be done, the finger may be put on *A* without effect.

These tongs are of great use in charging any body from a machine, or in connecting two conductors.

EXPERIMENT 121. **Residual charge of condenser.** Charge a Leyden jar, and leave it charged for a minute or two. Discharge it by means of the jointed discharger. After it has rested for a minute or two, bring up the discharger again and see if there is now any charge.

323. A jar acts as though there was a kind of 'soaking' of the electricity into the dielectric. This electricity is not able to get out when an opportunity is given to it, but it can 'soak out' when the force due to the main charge has been destroyed; this is called the *residual charge*. It is strongly marked in the case of glass and paraffined paper, but non-existent in air, and negligible in *mica*; hence one of these dielectrics is usually used for condensers which are rapidly charged and discharged (e.g. that of a Ruhmkorff's coil, p. 153).

EXPERIMENT 122. **Seat of the charge.** If a glass jar *B* (Fig. 187) is provided with a removable inner (*A*) and outer C (~~*B*~~) coating made of metal, we can determine where the charge on a Leyden jar is situated.

Put the parts *A*, *B*, and *C* together to form an ordinary jar, and

charge it by holding *C* in the hand, with the knob touching the conductor of a machine in action.

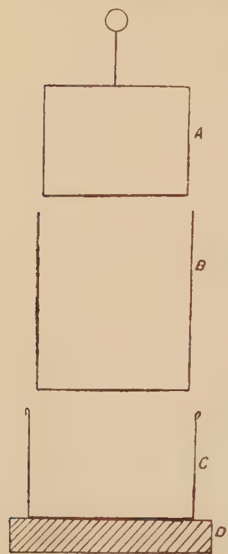


Fig. 187.

Stand the whole on an insulator *D*. You will now find that you can touch the knob of *A* without getting a perceptible shock, provided *C* is not touched at the same time †.

Lift *A* out by its knob. Then lift *B* out of *C*, and finally lift *C* from *D*. In none of these operations will you get a perceptible shock, even if you try to collect the electricity off the surface of *B*.

Put the jar together again, first standing *C* on *D*. Now see if the jar has any charge: if so, it must have been on or in the glass, since *A* and *C* are conductors.

Repeat the experiment, and see if you can perceive a spark when the finger and thumb touch the glass, one inside, the other outside, opposite to one another. You will be led to understand that the two charges are binding one another on opposite sides of the non-conducting dielectric.

324*. Hitherto we have for convenience looked on the charge as being on the conductor, but we have found that it only remains at rest on the *surface* separating the conductor from the dielectric; we now see reason to think that it is really on the *surface of the dielectric*, where it is in contact with a conductor (or, of course, on the surface of separation of two dielectrics such as air and rubbed ebonite).

We have seen that lines of force run through the dielectric between the opposite charges on its surfaces; so that what we have learnt by our experiments as to 'charges of electricity' has merely related to a *state of strain, or distortion, of the dielectric itself*, rather than to any material 'electron.' This state of strain can easily be imagined when the dielectric is a solid such as glass, which we can prove to be actually compressed by the electrification of its surfaces, as in a Leyden jar; but the dielectric

† See p. 250; *C* being insulated from the earth a very small loss of electricity from *A* will suffice to bring its potential down to zero, since the capacity of the body *A* is not artificially increased by the proximity of an earthed conductor.

may be a perfect vacuum. Hence we must fall back on the idea that this state of strain exists in the **ether** (the hypothetical medium pervading all space, by means of which light is transmitted). It may be supposed that the presence of glass or sulphur in the space occupied by this ether affects the extent to which it is strained, which accounts for these materials having each its own specific inductive capacity; and that the presence of a metal or other conductor makes it impossible for the ether in that space to be strained at all, the ether simply yielding.

325*. In the case of any dielectric, the electric forces producing the distortion may be too strong, and in that event the dielectric breaks down and a 'spark' passes. This happens easily in air and other gases at ordinary pressures; very easily indeed when the gas is at a low pressure, as we shall see subsequently (p. 257); but such a substance as glass will support a very large force, or in other words has a great '*dielectric strength.*' Thus glass forms an excellent dielectric for Leyden jars, as (1) it is a very perfect insulator, (2) it has a high specific inductive capacity, and so the condenser has a large capacity for a given area of coated surface and thinness of dielectric, and (3) it has a high 'dielectric strength.' It should be noticed that if a Leyden jar is made of very thin glass and is charged to a high potential, it is liable to be pierced by a spark, and it is then useless.

CHAPTER VIII

Miscellaneous Experiments

In this chapter we will consider some isolated facts, of considerable importance in themselves but not logically dependent on one another.

326. Connection between frictional and voltaic electricity. Faraday devised several experiments to demonstrate that frictional and voltaic electricity are really the same, though differing considerably in the degree in which they exhibit certain of their properties.

Experiment 123. Take a strip of blotting-paper, and moisten it with a solution of starch-paste (i. e. water in which a little starch has been *boiled*) in which are dissolved a few crystals of potassium iodide.

Lay it on a sheet of glass, and hold it so that the paper lies below the two knobs of an electric machine in action. These knobs should be about two centimetres apart and the paper about half a centimetre below them, as in Fig. 188, where *A* and *B* are the knobs, *C* is the starch-iodide paper, and *D* is the supporting sheet of glass.

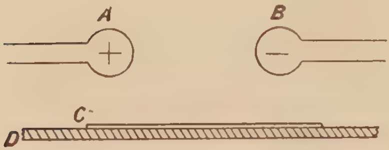


Fig. 188.

A series of sparks will pass from the knobs to the paper, and after a short time a dark-blue discolouration will be seen at each point where the sparks reach the paper. This is due to the liberation of iodine by the electricity, which produces a blue colour with the starch; an exactly similar process to the electrolysis described in Chap. XIV, Part II.

It will be noticed that whereas when the liberation is effected by the current from a cell, the blue colour only appears where the current enters the paper, in this case it appears at both ends. This proves that the discharge is an *oscillating* one, the + electricity passing first from the + to the − knob, but surging backwards and forwards very rapidly and very frequently in the extremely short time during which each spark lasts. Thus, although the amount of electricity passing with each discharge may be extremely small compared with that produced by a cell, this defect is made up by the number of journeys.

If the blotting-paper is only slightly moist, you may observe a difference in the shape of the two patches of discolouration, in spite of this oscillatory character of the discharge. Try to account for this by carefully examining the behaviour of the spark.

327. Volta's condensing electroscope. Volta proved the identity of the electricities produced by friction and by one of his cells, by making his cell affect an electroscope. If one pole of the cell is connected to the knob of an electroscope and the other pole to the cage, it will be found that even if a difference of potential exists it is not sufficient to cause a divergence of the leaves. In order to prove the existence of this difference of potential, he used a condenser * of con-

* See Chap. VII.

siderable capacity, which he charged from the cell by connecting each plate to one of the poles of the cell. The large capacity of the condenser was produced by bringing the plates very close together; and when they were charged by the cell (which was then disconnected from the plates) he moved the plates further apart, thus decreasing the capacity of the condenser and so raising the potential of one of the plates, as in Experiment 118. When this plate was connected to the electroscope, the potential was sufficiently high to be indicated, showing that the cell produced electricity capable of causing a difference of potential of the same kind as the electricity produced by friction.

EXPERIMENT 124. You will need a sensitive gold-leaf electroscope and a condenser consisting of a pair of parallel plates which are fairly true planes. One of these plates must be well insulated; this can conveniently be done by laying it on three piles of alternate 'lozenges' of ebonite and sulphur. This plate is connected to the knob of the electroscope. On this must be laid a piece of paper which has been soaked in melted paraffin wax and allowed to cool *.

On this sheet of paper is laid another plate as large as the lower one. It is convenient to have a handle fixed to this plate, and the cover of an electrophorus forms a very good upper plate, though the insulating handle is not really needed.

Some form of voltaic cell is taken, such as a Leclanché; the experiment is easier if several are joined in series to form a battery (see p. 101).

A copper wire from one of its poles, say the $-^{ve}$, is held against the upper plate, and that from the $+^{ve}$ pole against the lower plate, great care being taken to secure perfect metallic contact between plates and wire. This is so important that it is much more satisfactory to have a binding screw soldered to each plate, to which the wire may be attached; but if a small patch of each plate is rubbed with emery paper and the wires simultaneously pressed against these patches, good contact can be obtained. On no account must the wires be merely touched on the lacquered surface of the plates, since the difference of potential produced by the cell is too feeble to

* The wax should not be heated much above its melting point, or its insulating properties become impaired. The heating should be done in a dish in a hot-air oven or over a water bath, and the paper, previously well dried, left in it sufficiently long to allow all bubbles of air to escape. The paper is then hung up to drain off superfluous paraffin.

This provides a dielectric of high specific inductive capacity and very high insulation.

overcome obstacles which are easily broken down by the electricity produced by friction.

The $-^{ve}$ pole of the cell is to be connected by a wire with the cage of the electroscope, and this connection is to be left intact throughout the experiment.

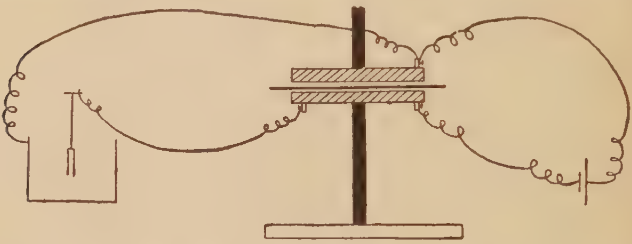


Fig. 189. Condensing Electroscope.

After good simultaneous contact has been secured between the plates and their respective poles the wire is removed from the insulated plate, great care being exercised that the finger does not touch the binding screw after the wire has left it *.

Now raise the upper plate, and observe whether the consequent decrease of capacity of the condenser has raised the potential of the charge on the lower plate sufficiently to affect the electroscope.

If so, test the sign of the electrification by bringing up a body charged with electricity of a known sign, and so determine the sign of the electricity given off by the $+^{ve}$ pole of a battery.

The difference of potential between the poles of the cell is shown by the Quadrant Electrometer (see p. 281) much more easily than by the condensing electroscope.

328. If a sufficient number of cells are joined in series, and sufficient attention is paid to the insulation of the supports of each cell, the potential difference between the terminals of the battery becomes great enough to cause sparks to pass between them when held near together, and all the phenomena of statical electricity can be reproduced.

* So long as the wire from the + pole is connected to the plate, the cell will easily supply all the electricity that leaks away through the body, but after this wire is removed a touch with the finger will bring the potential of the plate to zero ; therefore give the binding screw or cleaned part of the plate a touch with the wire before finally taking it away.

Thus an E.M.F. of 1,000 volts, produced by about 500 accumulators, will spark across about $\frac{1}{200}$ of an inch, and in order to spark through 5 cms. of air at the ordinary pressure, about 150,000 volts are required. This must not be confused with the case of the ordinary 'arc'; if an E.M.F. of 1,000 volts is maintained between a couple of platinum balls, and these are brought within $\frac{1}{200}$ of an inch of one another *without ever touching*, a steady stream of flame bridges the gap; while if only 50 volts are maintained between two pieces of carbon, if these are *first touched together* and then separated, a steady electric discharge passes across the gap.

329. Discharge through gases at reduced pressure. If we have a glass tube, such as is shown in Fig. 190, A and B being platinum wires sealed through the glass, and C a screw to fit the plate of an air-pump, we shall find that an electric machine is incapable of passing a spark from A to B if this length exceeds 5 or 6 inches. If however the air is partially removed from the tube by means of the pump, at a certain stage of the exhaustion sparks begin to pass, and when a good vacuum is reached we get a continuous glow filling the tube, instead of a defined spark. If pumping is continued until a very perfect vacuum is made, no discharge at all will pass through the tube, the spark going by preference over the outside, between A and B.

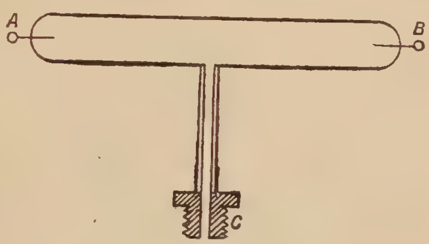


Fig. 190.

When the vacuum is just short of being an insulator, the discharge produces Röntgen rays, as may be seen by using a fluorescent screen covered with barium platinocyanide (see p. 190).

EXPERIMENT 125. The glow discharge through a vacuum can be produced very easily by taking an ordinary electric-light glow-lamp, and putting its cap against one of the knobs of a machine in action, holding the glass bulb in the hand. An old glow-lamp of which the filament is broken will serve; the experiment is liable to damage the filament or the insulation of a new one.

This experiment must of course be performed in the dark; a

flickering glow will be seen to permeate the bulb, and after the cap of the bulb is removed from the knob, this discharge will go on again if the finger is brought near the cap, or the cap is earthed, since the inner surface of the glass has been charged. Hence care should be taken in laying the lamp on the table, or an unexpected shock may be obtained ; this will be prevented if the glass is held in two fingers while laying it down, as then only a very small part of the outer surface will be discharged.

EXPERIMENT 126. **Wind from an electrified point.** Support a needle on an insulating stand so that its point projects, as in Experiment 112, and connect the needle to one knob of a machine in action.

Light a candle and hold it so that the flame is about half an inch from the point and in a direct line with the needle ; this will serve to show if there is an actual wind proceeding from the electrified point, as asserted on p. 236.

The presence of an earthed conductor on the further side of the flame will increase the effect.

330. Atmospheric electricity. In the year 1752 Benjamin Franklin, noting that lightning showed very many of the properties which he had observed to be possessed by electric sparks, sent up a kite during a thunderstorm. When the string had become a conductor by being wetted, he succeeded in drawing sparks from a key which he had attached to the string, and in charging a Leyden jar with the electricity. He had, for safety, tied the end of the string to a silk ribbon, which fortunately did not get wet. A Russian named Richmann was killed the next year while carrying out a somewhat similar experiment ; he collected the electricity by a lightning-conductor with a pointed top, whose lower end was brought into his laboratory.

The particles of water which make a cloud are nearly always charged more or less highly ; it is probable that all atmospheric electricity is produced by winds causing friction of the various solid and liquid particles in the air against one another and the earth and sea.

Lord Rayleigh noticed (in 1879) that if he electrified a jet from which was issuing a stream of fine drops of water, the drops coalesced. This may explain the large size of the drops that fall during a thunder-shower.

331. Thunder. Since the spark which constitutes the 'flash of lightning' may be anything up to about a mile long, and since sound

takes about five seconds to travel one mile, we should not expect to hear after a flash the same short, sharp crack that we hear in a laboratory. The sound in either case is probably produced by the sudden heating of the air, through which the spark passes. This produces a sudden expansion, followed by a collapse on cooling. The track of the spark is commonly observed to be very crooked, and often ramified, and each branch would give rise to a sound reaching the observer at a separate time.

Thus even in the absence of clouds, a rolling sound might be expected, and the reverberations of the thunder must be much increased by reflection from the dense clouds characteristic of a thunderstorm.

332. Lightning-conductors. The purpose of these is twofold. First, by means of their pointed ends they have an opportunity of quietly discharging the electrification of the air and clouds above them; for this purpose they must have an excellent connection to 'earth,' and this should be secured by carrying them down into the middle of a sackful of coke buried in a damp place.

Second, they offer an easy path for a spark that actually strikes a building. All masses of metal on the outside of the house, such as spouts and lead roofing, should be connected to the conductor, but not to pipes, &c., inside the house. As mentioned on p. 229, since rapidly oscillating discharges do not traverse the inner layers of a conductor, but keep to the skin, flat bands are better than rods. These may be nailed direct to brick walls, ordinary insulators not being needed since the laws obeyed by such currents are not the same as for steady currents. For example, the discharge will overleap a short air-gap in preference to passing round a very circuitous route along an excellent conductor, such as a coil of wire.

This latter principle is used to safeguard people using a telephone during a thunderstorm. On its way from the overhead line to the instrument, the telephone wire passes close to a metal 'comb' in direct connection with the earth, and is then wound into a coil. Ordinary currents pass through the coil to the instrument, but if a flash of lightning strikes the overhead line at any point, it leaps across the air-gap to the comb, and so to earth.

333. Duration of a spark. The time during which a single spark-discharge persists is extremely small, as may be seen by merely producing in a dark room occasional long sparks by means of a Voss

or Wimshurst machine fitted with a Leyden jar to each terminal. Although the plate with its sectors may be rotating very rapidly, it seems to be standing still when seen only by the light of the spark, showing that it has not been able to turn far enough to blur the image on the retina before the light has ceased *.

As a matter of fact, a spark does not consist of a single passage of electricity in one direction only, but of a surging to and fro of the electricity from one knob to another, which may take place many times. This can be seen by photographing the spark on a sensitive plate moving rapidly behind a lens. Each surging of the electricity will give a separate clear image.

By employing a mirror turning on an axis at a known speed it is not difficult to measure the actual duration of the discharge. In one experiment of this kind, Wheatstone found that the discharge from a certain Leyden jar lasted $\frac{1}{24000}$ of a second.

A flash of lightning probably lasts rather longer.

CHAPTER IX

Elementary Theory of Electrostatics

334. The following chapter contains some of the more elementary parts of the theory of electrostatics. Hitherto we have pursued the subject experimentally, and the results of the experiments have led us to formulate certain general laws, such as that relating to the absence of force inside a charged conductor. We must now, however, apply the methods of mechanics, and the student will have to face difficulties of an entirely different kind from those encountered up to this point; the non-mathematical student will find these difficulties more considerable, although the mathematics required is only 'such as is ordinarily taught in schools.' The definitions and propositions which follow are of great importance and should be studied with care, since they will serve to give precision to the somewhat vague ideas that may have been formed as to potential, &c.

* The spark seems to us to last longer, as an image produced on the retina remains uneffaced for about $\frac{1}{10}$ of a second; this is the reason why a cinematograph appears to give a continuously-moving picture.

335. Law of force between two charged bodies. We have, on p. 243, decided on a measure of the unit quantity of electricity, based on the repulsion between two such quantities. We have, on p. 231, described a method of obtaining any required multiples of such units; but we have not as yet investigated the manner in which the force of repulsion between two charges depends on the number of units in each charge, nor on the number of centimetres intervening between the charges. We have, however, on p. 193, seen reason to believe that this force lessens as the distance is increased, a fact discovered by Henry Cavendish (1731–1810). The research into this question was pursued by Coulomb (1736–1806); he devised an apparatus, called a *Torsion Balance*, for the purpose of measuring mechanically the exceedingly weak forces between small spheres carrying small charges.

One of the charged balls was supported on the end of a long thin horizontal rod of shellac, supported at its middle point by a thin silk fibre. The other charged ball was brought near it in such a position that its repulsion tended to make the rod turn horizontally round its centre, twisting the fibre, and the top end of the fibre was then twisted backwards through such an angle as to force the shellac rod back to its former position in spite of the repulsion of the charged ball. The angle of twist of the fibre gave him a measure of the exceedingly small force needed to effect this, so that he could compare the forces exerted by the charged ball at various distances from the movable ball, and also when its own charge was varied.

He found that if he doubled the charge on the fixed ball, the force of repulsion was doubled; if he trebled it, it was trebled, and so on; the same result occurred when he varied the charge on the movable ball. He also found that if he kept everything else the same but doubled the distance between the balls the force was not halved, but reduced to $\frac{1}{4}\left(\text{or } \frac{1}{2^2}\right)$ of its former value; if the distance was trebled, the force was reduced to $\frac{1}{9}\left(\text{or } \frac{1}{3^2}\right)$, and so on.

336. The law which his experiments suggested was that the *force between two charges is directly proportional to the product of these two charges, and varies inversely as the square of the distance between them.*

We may express the law in symbols thus: if two charges of q and

q' units are situated **in air** at a distance of r cms., the force of repulsion between them is $\frac{qq'}{r^2}$ dynes*.

If the charges are of opposite sign, the signs of q and q' differ, so that their product is negative, indicating an attraction.

337. Indirect proof of the above law of force. This law, usually called the Law of Inverse Squares, so commonly applies to the forces of nature that it is frequently called the Law of Nature. Exactly the same law applies in almost the same words to the attraction of gravitation, as was discovered by Sir Isaac Newton; and in that case the force between such masses as we can handle is so extremely small that it is hopeless to attempt, even with a delicate torsion balance, to establish the law. Newton proved that the law holds throughout the whole universe by the following indirect means: assuming the law to hold for every particle, he calculated mathematically the manner in which the moon and planets should move; he found that they moved in this manner, and proved mathematically that no other law of attraction between the particles would result in such movements.

The same indirect method of proof is applicable to the law of inverse squares in electrostatics, and was so applied by Henry Cavendish. We have seen, on p. 227, that electricity is confined to the surface of a conductor, and, on p. 225, that it is uniformly distributed over the surface of a sphere far removed from other bodies. We have also seen, on p. 232, that there is no electric force in the space included in a hollow sphere (or other conductor).

Now it admits of rigorous mathematical proof that a uniformly thick spherical shell of attracting (or repelling) material exerts no resultant force at any point of the interior space if, *and only if*, the law of attraction between separate portions of the material be that of 'inverse squares.' (See Arts. 338 and 339.)

It therefore follows that electric charges obey the law of inverse squares.

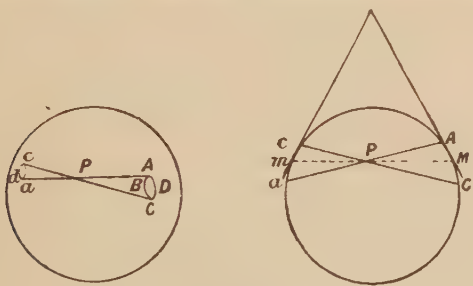
Thus, by mathematical reasoning applied to experiments with large charges spread over large areas, we indirectly establish a law dealing

* It is to be noted that if the two particles carrying the charges q and q' are immersed in a medium (e. g. turpentine or petroleum) whose specific inductive capacity is K, this force becomes

$$\frac{qq'}{Kr^2} \text{ dynes.}$$

with the mutual attraction of small charges concentrated at two points. In this case the experiments are simple and admit of a very high degree of accuracy, but the theoretical reasoning is somewhat involved; Coulomb's direct proof of the law is very simple theoretically, but the experiment is extremely difficult and only accurate enough to suggest the law.

338*. No force inside a charged sphere, assuming the law of inverse squares. Suppose a point P (Fig. 191 (i)) situated inside a sphere uniformly charged with + electricity, and consider the repulsion on a small + charge at P produced by the charge residing



(i) Fig. 191. (ii)

on an area $A\,B\,C\,D$ of the sphere, which is small enough to be treated as a plane surface. The charge at P must be *imaginary*, or so small that it will not by its induction alter the distribution of charge over the sphere.

Draw straight lines from the boundary of $A\,B\,C\,D$ to P and produce them to cut the sphere again at $a\,b\,c\,d$, marking out another small element of the surface; these two elements then form the ends of a double cone having its vertex at P. We will consider the repulsion on P of the charges on these elements.

Fig. 191 (ii) represents a section through the centre of the sphere and the central line $M\,m$ of this cone. Since the section of a sphere is a circle the tangents at M and m are equally inclined to $M\,m$ †, i. e. the elements $A\,B\,C\,D$ and $a\,b\,c\,d$ are equally inclined to the axis $M\,m$ of the cone.

Hence, although these sections of the cone are oblique sections,

† A deduction from Euc. III. 36.

their areas bear to one another the same proportion as do sections ($A'BC'D$ and $a'bc'd$, Fig. 192) through M and m, which are at right angles to the axis Mm, i.e. *normal sections* of the cone.

Fig. 192

This is the case because the area of each normal section is got by multiplying that of the corresponding oblique section by the cosine of the angle between the oblique and the normal section, and this angle is the same for $ABCD$ and $abcd$.

Now the areas of these normal sections through M and m are to one another directly as the *squares* of PM and Pm, since they are normal sections of the same right cone.

Therefore the small areas cut by the cone from the surface of the sphere are to one another directly as the squares of the distances of P from those areas.

But the electrical charges on $ABCD$ and $abcd$ are in the direct proportion of their areas, since the surface density is uniform. If then we assume the law of inverse squares (i.e. that the forces of repulsion, at P of *equal* charges on M and m, vary inversely as the squares of PM and Pm), it follows that the forces of repulsion of these charges will exactly balance each other at P (being equal in amount and acting in opposite directions along the same straight line MPm).

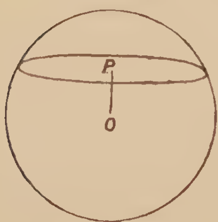


Fig. 193.

If now we fix on any definite plane through P, e.g. that perpendicular to the radius OP (Fig. 193), we can cut out the surface of the sphere on one side of the plane into a number of elements; and if we form cones having their vertices at P and these elements as bases, they will when produced beyond P cut up the whole of the rest of the sphere into corresponding elements. We have shown that if we assume the inverse square law, then each pair of elements has no resultant force at P, so that the whole charged surface can have no resultant force at P.

339*. We see then that, assuming the truth of the law of inverse squares, there can be no force inside a hollow charged sphere; the same method of proof cannot be applied to prove the absence of force inside a conductor of any other form, since the distribution of charge over its surface is not uniform.

But it can easily be shown by the above method that for a sphere *no other law* than that of the inverse square of the distance would give us this absence of force within a sphere. Hence, since the general experimental law that 'there is no force within a conductor' must be true for the particular case of a sphere, we are enabled to prove by elementary mathematics that the law of inverse squares must hold true in this case. It therefore holds true in all, since the manner in which the charge is arranged does not affect the force exerted by any one element of that charge.

340. Potential. Suppose that we have a body A charged with + electricity; for the present we will assume that it is far distant from any other charged body. Let P and Q be two points in the neighbourhood of A, $A\,P\,Q$ being a straight line; then, if we put a very small sphere charged with a unit quantity of + electricity at either P or Q, it will be acted on by a force of repulsion from A, which is greater at P than at Q. In order to make this charged sphere move slowly from Q to P we shall have to exert a force, and consequently *do work* on the sphere. By the definition of 'work,' as given in text-books of mechanics, the work done by a force when the point of application of that force moves in the direction of the force is measured by the product of the force into the distance moved; this is an easy quantity to compute if the force is constant, but in this case it is not, and the method of overcoming this difficulty is explained on p. 267.

The work so done is stated in *ergs*, an *erg* being the work done by a force of one dyne when its point of application moves through 1 cm.

For the present it is enough for our purpose to realize that to bring a + charged particle nearer to a + charged body requires the expenditure of work; and *that quantity of work which is needed to bring a particle charged with unit quantity of + electricity from an infinitely distant point up to the surface of a conductor is called the* potential *of that conductor.*

341. In the above definition of the potential of a body the 'infinitely distant point' (which is brought into the definition only because

the charged body exerts no force there) is, as a matter of practice, 'any point connected to earth.' This amounts to the same, since no force is needed, and therefore no work is expended, in moving a charged particle about in the earth, so that the charged particle can be brought up from the other side of the earth to the nearest 'earth' without requiring the expenditure of any work.

342. It will be seen that if the charged particle is at P, it could itself do work in moving slowly to Q, so that the definition of potential of a body could be put as 'the work done by a particle charged with unit quantity of + electricity in travelling from the surface of the body to earth.' In this way of stating it, it is easy to see that we have merely given a precise and mathematical form to the definition of potential on p. 214.

It must be noted also that if the charge on A be $-^{ve}$, work will be done *by* the charged particle in going from Q to P; this shows that A in that case is of '$-^{ve}$ potential.'

Observe that we can now assign a definite meaning to 'potential at a point of space'; it is the work that must be done to bring a particle charged with unit quantity of + electricity up to that point from 'earth.'

343. It can be proved mathematically, by methods of proof either too advanced or too lengthy to be given here, that a quantity of attracting matter uniformly distributed over the surface of a sphere (provided the force between particles follows the law of inverse squares) will exert the same force on a particle placed at any point outside the sphere, as if the whole of the attracting matter were concentrated in one point at the centre of the sphere.

We will assume the truth of this, but it must be clearly understood that we have neither proved it mathematically, nor demonstrated its truth experimentally in any particular case.

344. Potential at any point of space due to the charge on an isolated charged sphere. It can be shown, by a simple mathematical proof (see Art. 345) assuming the statement in Article 343, that if a quantity $+q$ of electricity be distributed over the surface of an isolated sphere, the potential at a point in the neighbourhood of the sphere caused by this charge is $\frac{q}{r}$, where r cm. is the distance

of the point from the centre of the sphere, i. e. that it needs work to the extent of $\frac{q}{r}$ ergs to bring a particle carrying a unit charge from the earth to the point P against the repulsion of the charge on the sphere.

345*. Proof. Draw a straight line passing through the centre of the sphere. Let B, C (Fig. 194) be two points on this line, and Q, R, S, T be points very near together.

Fig. 194.

If q is the charge on the sphere, the force on unit + charge at Q is $\frac{q}{AQ^2}$, and that at R is $\frac{q}{AR^2}$; but as Q and R are very near together, we may take these quantities as so nearly equal that the force throughout the length QR may be taken to be

$$\frac{q}{AQ \cdot AR},$$

since that is the geometric mean between the values at the ends of QR.

Hence the work done in pushing a unit charge from R to Q is

$$\frac{q}{AQ \cdot AR} \times QR,$$

or,
$$\frac{q}{AQ \cdot AR}(AR - AQ),$$

or,
$$\frac{q}{AQ} - \frac{q}{AR}.$$

Similarly the work done in coming from S to R is

$$\frac{q}{AR} - \frac{q}{AS},$$

and from T to S is

$$\frac{q}{AS} - \frac{q}{AT}.$$

Then the total work done in going from T to Q is the sum of these, and we see that, on adding up these values, one term of each cancels one of the next, leaving only $\frac{q}{AQ} - \frac{q}{AT}$.

Thus, if we divide the whole distance between B and C into an enormous

number of such short distances, and add together the work spent in pushing the particle through each, the final result comes to

$$\frac{q}{AB} - \frac{q}{AC}.$$

This gives the difference of potential between two points B and C.

If C is at an infinite distance, AC is so large that $\frac{q}{AC}$ is indefinitely small, and the *potential at the point* B is given by the expression

$$\frac{q}{AB}.$$

346. Capacity of a sphere. We can now determine the actual capacity of an isolated sphere (i.e. one situated in air and far removed from any other conductor, charged or uncharged).

Suppose that the sphere has its centre at A (Fig. 195) and a radius R cm.; give it a charge of Q units. By Article 345 the potential at an outside point distant r cm. from the centre is $\frac{Q}{r}$.

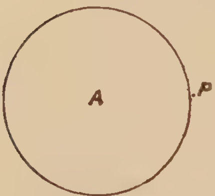


Fig. 195.

Consider this outside point (P) as being situated just outside the sphere, indefinitely near to the surface, then the potential there will be $\frac{Q}{R}$, since P is now at a distance R cm. from the centre.

But the potential at P differs indefinitely little from the potential of the surface of the sphere close to P; and the potential of the sphere is the same throughout (p. 219), so that the potential of the sphere is $\frac{Q}{R}$.

Hence a charge Q given to a sphere of radius R cm. raises its potential to $\frac{Q}{R}$; so that a charge of R units would raise its potential to $\frac{R}{R}$ or 1. But (see p. 244) the definition of Capacity of a body is 'the number of units of electricity which are needed to raise its potential from zero to unity.'

Hence *the capacity of an isolated sphere is equal to its radius* (*in centimetres*).

347. Distribution of a charge between two spheres con-

nected by a thin wire. As an illustration of the result of Article 346 we may consider the case of two spheres of radii r and r' cm., situated far apart and connected by a thin wire.

We have defined the capacity of a body as being the quantity of electricity needed to raise the potential of that body by unity. When two conductors are joined by a wire so as to form one conductor the potential is the same throughout (Experiment 100), hence it makes no difference to the quantity of electricity that must be given to each body, whether or not they are connected together, provided the potential of each has to be brought up from zero to unity. Hence the capacity of such a combined system must be the sum of the capacities of its separate members.

Suppose that a total quantity Q is imparted to the combined body; its capacity being $(r+r')$, the resulting potential (V) will be

$$V=\frac{Q}{r+r'}.$$

The separate capacities of the spheres are r, r', and they are each raised to a potential V; if we call the respective charges q and q' we shall have

$$V=\frac{q}{r}$$

$$\text{and} \quad V=\frac{q'}{r'},$$

$$\therefore \quad \frac{q}{r}=\frac{q'}{r'};$$

or, *the charge is shared by the two spheres in direct proportion to their radii.*

Next consider the surface-density on each of the two spheres.

The area of surface of a sphere of radius r cm. is $4\pi r^2$ sq. cm.

The charge on the first sphere being q units, the charge per sq. cm. is $\frac{q}{4\pi r^2}$ units.

Now we have shown that

$$V=\frac{Q}{r+r'}$$

$$\text{and} \qquad V=\frac{q}{r};$$

$$\therefore \qquad \frac{q}{r}=\frac{Q}{r+r'};$$

$$\text{or,} \qquad q=Q\frac{r}{r+r'}.$$

Hence the surface-density on the first sphere is

$$\frac{Q\frac{r}{r+r'}}{4\pi r^2} \text{ or } \frac{Q}{4\pi r(r+r')}.$$

348. This result is of importance in the case when the radius (r) of the sphere is very small indeed, for then the denominator becomes very small, and hence the value of the surface-density on the small sphere very large, although the total charge given to the system is not large.

We have previously stated the experimental fact that if the surface-density exceeds a certain limit in dry air (about 8 units per sq. cm.) the electricity will discharge itself by convection through the air. These two facts taken together explain the action of sharp points in discharging conductors, since the point of a needle may be looked on as a hemisphere of extremely small radius.

We have here an illustration of what was noticed in Experiment 103, that the surface-density is not necessarily constant over a conductor.

349. Equipotential surfaces round a charged sphere. Imagine a sphere situated in air far from other conductors, having its

Fig. 196.

centre at A; and let it be charged with q units of electricity. If P is a point outside the sphere, at a distance l cm. from A, the potential at P will be $\frac{q}{l}$.

This potential will have the same value at all points of the surface of a sphere having its centre at A and passing through P, since l is the same for all points on this sphere; hence this sphere is said to be an

equipotential surface of the field of force due to the charged spheres.

Suppose that Q is another point in the field of force at such a distance from P that it needs exactly unit quantity of work (i. e. one erg) to make a particle, charged with unit quantity of + electricity, move from Q to P. There will be a similar equipotential surface through Q; we can cut up the whole space surrounding A by a series of such equipotential surfaces, which will all be spheres having their centres at A, and at such a distance apart that there is an increase of one erg in the potential between any two consecutive surfaces.

These surfaces will not be at equal distances from one another, but their distance apart will increase with their distance from A, as in the diagram (Fig. 196).

350. It will be seen that the *lines of force* due to the charge on the sphere are all radial straight lines directed outward from A (since the force at any external point due to the electricity on the sphere is the same as if the whole charge were concentrated at A); and we know that all radii of a sphere meet the surface at right angles; hence in this case the lines of force always meet the equipotential surfaces at right angles.

From this last fact we see that if a charged particle is moved from point to point over this surface, since the movement is always at right angles to the direction of the force at the point, the displacement of the point of application of the force *in the direction of the force* is nil. So by the definition of work (p. 265) none is done.

351. Equipotential surfaces for any distribution of the charge. It is easy to imagine the space, surrounding any system of conductors carrying charges of electricity, mapped out in a similar manner by a series of equipotential surfaces, so chosen that one erg is needed to force a unit charge from one surface to the next.

But in the vast majority of cases the form of the equipotential surface is exceedingly complex. However the case of the surfaces between two parallel planes, one charged, the other earthed, is simple and useful; it will be considered in Article 360.

352. It is true in the general case, as in the case of the spheres, that the lines of force must cut the equipotential surfaces at right angles to those surfaces; otherwise the force at a point of the surface

would have a component along the surface, so that some work would be done on a charged particle moving along the surface, and in that case the potential at one point of the surface would be higher than at another; this by definition is not the case.

Thus we can imagine the whole space round any system of charged bodies cut up by a series of equipotential surfaces traversed by lines of force always cutting the surfaces at right angles.

These surfaces and lines of force have an actual physical meaning, and are not a mathematical abstraction. They indicate the manner in which the dielectric is strained as the effect of electrical charges.

353. Tubes of force. Revert once more to our illustration of the charged sphere. We may select a small area, $B\,C\,D\,E$, on the equipotential surface through P (Fig. 197), and draw all the lines of force passing through the boundary of that area. These lines will form a kind of tube (in this case a cone with its vertex at A), which cuts out a similar area from each of the other equipotential surfaces.

Fig. 197.

Such a tube is called a **tube of force**, and the size of the area $B\,C\,D$ is not taken haphazard, but is so chosen that the product of the force at P (on a unit + charge, measured in dynes) by the area $B\,C\,D$ (measured in sq. cm.) is *unity*.

Thus if the force on a unit charge at the point P (or the 'force-intensity at P') is F dynes, the area of the cross-section of the tube at that point will be $\frac{1}{F}$ sq. cm.

354. It can be shown by mathematical reasoning that if the size of the tube of force is so chosen at any one point that this connection holds between the force-intensity and the area of cross-section of the tube at the point, then the same relation holds all along the tube. Thus we see that if the lines of force, which form the walls of the tube, spread out from one another, so the force-intensity must diminish; and, where the tubes are straight-sided, forming cylinders, the force is constant along them.

355. Number of tubes of force radiating from unit charge. Suppose that a unit + charge is situated at A, in air far from other charges, and that P is a point 1 c.m. from A. Then the force on unit charge at P would be $\frac{1}{1^2}$ dyne or 1 dyne, so that the area of cross-section of the tube of force passing through P must be 1 sq. cm. at that point.

Draw a sphere having its centre at A and passing through P; this will be an equipotential surface. Its area is $4\pi \times 1^2$ sq. cm., so that there must be in all 4π tubes cutting this sphere, since each has to cut 1 sq. cm. from the surface; hence, *each unit charge gives rise to* 4π *tubes of force.*

If there is a charge $+\rho$ at A, the force at P is $\frac{\rho}{1^2}$ dynes, so that the area of each tube of force must be $\frac{1}{\rho}$ sq. cm., and therefore $4\pi\rho$ tubes having this cross-section will be needed to occupy 4π sq. cms., the surface of the sphere.

Hence *from a charge containing* ρ *units* $4\pi\rho$ *tubes of force proceed.*

If the charge at A is negative, the only difference will be that the tubes will proceed towards A instead of from A.

356. When A is situated in free space, these tubes of force will be

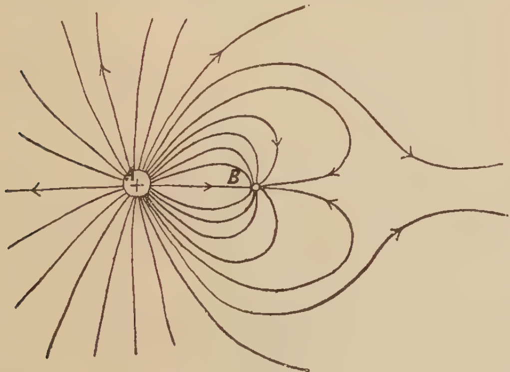


Fig. 198.

distributed uniformly round the point, and will ultimately reach some other conductor at the points where the charges induced by A happen

to be situated, each tube of force ending as it began on a charge of magnitude $\frac{1}{4\pi}$, but negative. If, however, A is near to another conductor, the tubes of force will be pulled out of their uniform distribution, as for example in Fig. 198, where the central lines of some of the tubes are indicated for a charge of 4 units near a charge of -1 unit, in free space.

357. Condition of the dielectric. Faraday's conception of the tubes of force, traversing the dielectric between the charges on the boundaries of that dielectric, enables us to get a clear and vivid mental picture of the processes going on in that medium.

We have to think of the whole of the dielectric in the neighbourhood of the charged bodies as being cut up by these unit tubes of force; cutting across the tubes at right angles to them are equipotential surfaces, spaced apart at such distances as explained in Article 349. Thus the dielectric is parcelled out into a multitude of small cells.

Now in order to separate the opposite charges which lie on the bodies at the two ends of any tube of force, a certain amount of work had to be done, which remains in the system as potential energy. This energy may reasonably be considered as residing in the dielectric along the tube of force joining the charges, and we can imagine it distributed along that tube in such a way that each small cell gets an equal share. If this is done for each tube, it can be shown mathematically that *every cell* in every tube of force, no matter how complicated the system of charged bodies may be, will get *an equal share of energy*; so that the dielectric is by this means cut up into cells, each of which contains the same fraction of the total energy residing in the whole system. We do not know the state of the dielectric that enables it to store potential energy; but it seems certain that the tube of force forms the boundary of the piece of dielectric which is concerned with transmitting the electric force between the charges at its ends, and stores up the energy of separation of those charges.

358. Again, Faraday showed that all the mechanical actions between the various bodies carrying charges are explained, if we assume that the tubes of force act like stretched india-rubber strings, exerting a *tension along their length*; and since a fluid dielectric such as petroleum or turpentine would not be in equilibrium under such a system of tensions along lines within it, it is necessary to imagine in

addition a *hydrostatic pressure outward* perpendicular to the surface of each tube. Thus each tube must be thought of as trying to shorten itself and to swell laterally at the same time.

359. To illustrate the effect of such tensions along tubes of force, let us briefly consider one or two cases.

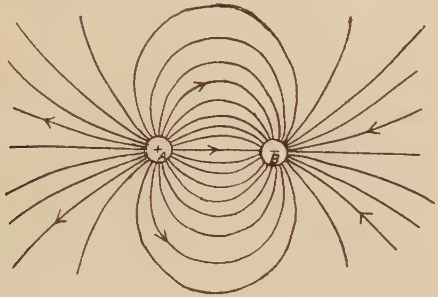


Fig. 199.

In the case of two oppositely charged spheres, *A* and *B*, the tensions obviously pull them together (Fig. 199).

In the case of two similarly charged spheres (Fig. 200) we see that

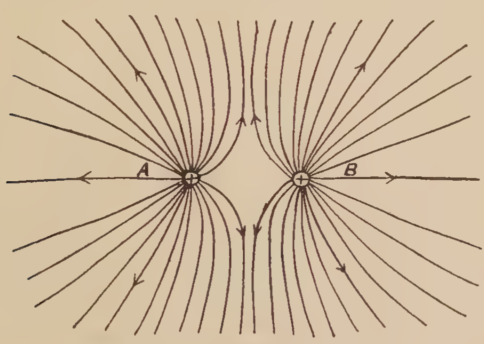


Fig. 200.

there are many more tubes leaving them on the outer sides than on the sides facing the other sphere; so that the spheres are *pulled* by the lines of force away from one another towards the distant objects

on which the tubes end. At the same time the outward pressure of one tube on the next may be looked on as assisting in the repulsion.

Fig. 201 shows the distribution in the field of force caused by a charged body (A) when an uncharged body (B) is near it.

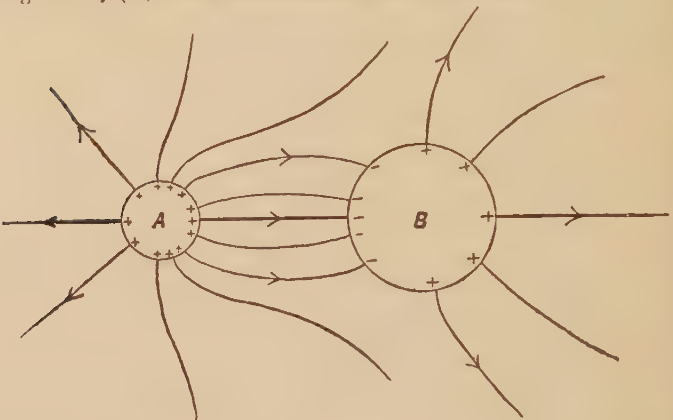


Fig. 201.

The lines entering B on the side towards A are seen to be so situated that they exert a more effective pull on B than the lines leaving it on the other side, though there are an equal number of them. Thus on the whole B is urged towards A, and A is itself urged towards B by the lack of symmetry in the distribution of the lines leaving it (cf. Fig. 23).

The shapes of the lines from A which do not actually reach B are affected by its presence, owing to the lack of pressure from the other lines of force which do reach it.

360. Force at a point between two large parallel plates near together. Let A and B (Fig. 202) represent two parallel

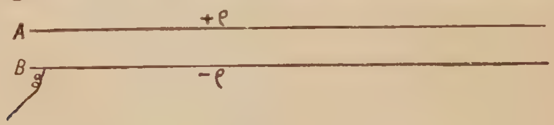


Fig. 202.

plates, and let the plates be both of very large area in comparison with the distance between them, so that we need not consider the

irregularity of distribution near their edges to have any effect in the part with which we are concerned.

Let the plate A be charged with electricity to such an extent that there are $+\rho$ units on each square centimetre, and let B be earthed. We will assume that all other conductors are so far distant from A that all the tubes of force starting from A must pass across to B (i.e. that we are dealing with a condenser isolated from other bodies); then, from the uniformity of the conditions, the lines of force between the plates must all be parallel to one another and at right angles to the plates.

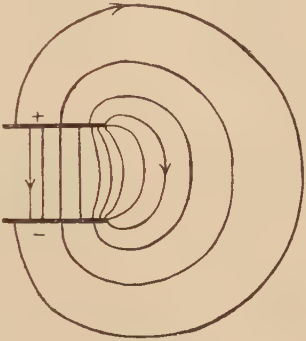


Fig. 203.

The lines of force will of course not be parallel near the edges of the plates—they will bulge out there and some will pass from the back of the plates, as in Fig. 203; but we are not concerned with the edges at present.

Since there are ρ units on each sq. cm. of A, $4\pi\rho$ tubes of force must start out from each sq. cm., so that the area of each tube must be $\dfrac{1}{4\pi\rho}$ sq. cm.; hence the force-intensity must be $4\pi\rho$, since the product, force-intensity by area of cross-section, must be 1. This force must be constant at all points of the space between the plates.

So that at all points between two large parallel plates, close together, one charged with surface-density $+\rho$, the other with surface-density $-\rho$, the force on unit charge will be $4\pi\rho$ dynes.

361. Difference of potential between two parallel plates. Suppose that the plates of Article 360 are d cm. apart. Then the work done in pushing a particle charged with unit quantity of + electricity across from B to A is

$$4\pi\rho d \text{ ergs},$$

since the force at any point is $4\pi\rho$ dynes, and the distance traversed is d cm.

But this work is, by definition, the difference of potential between the plates; so that if B is earthed the potential (V) of A is $4\pi\rho d$.

Hence, since the charge per sq. cm. is ρ units, the capacity of the condenser *per sq. cm.* is

$$\frac{\rho}{4\pi\rho d}, \text{ or } \frac{1}{4\pi d}.$$

Thus, if we may neglect the irregularity caused by the edges, the capacity of a condenser formed by two parallel plates of area A sq. cm. and distant d cm. from one another is

$$C = \frac{A}{4\pi d}.$$

362. If the dielectric between the plates is not air, but a medium whose specific inductive capacity is K, the capacity becomes

$$C = K \times \frac{A}{4\pi d},$$

since the specific inductive capacity was defined, on p. 248, as the number by which the capacity of a condenser having air as its dielectric must be multiplied in order to obtain the capacity of the same condenser with this substance as its dielectric.

Thus when we know the coated area of surface, the thickness, and specific inductive capacity of the glass of a Leyden jar, we can calculate approximately its capacity.

363. Attraction between the plates of a condenser. We have hitherto been considering the force on an imaginary unit charge situated between the plates of a condenser; let us now consider the actual force of attraction of one plate on the other.

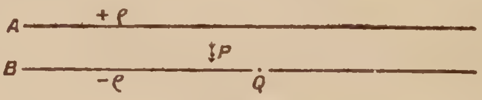


Fig. 204.

At a point P between the plates, the total force was found to be $4\pi\rho$; but this force must have been made up of a repulsion from A and an attraction towards B. As A and B are charged to the same surface-density, these forces must be equal, so that each must be half of $4\pi\rho$, or $2\pi\rho$.

Now consider the force on a unit + charge, situated at a point Q, which lies in a small hole in B, exactly in the plane of B. This cannot experience an attraction towards B, since it is in its plane, and

it would be attracted back to its present position if it was moved in either direction from that plane.

Hence the only force on Q is the repulsion from A, which we have seen is $2\pi\rho$ dynes.

Hence the force at Q is a repulsion $2\pi\rho$ dynes on a unit charge, or $2\pi\rho \times \rho$ or $2\pi\rho^2$ on a charge $+\rho$, and therefore an attraction $2\pi\rho^2$ on a charge $-\rho$.

This then must be the attraction on the charge on each sq. cm. of B. If the area of B be S sq. cm., the attraction (F) will then be

$$F = 2\pi\rho^2 S \text{ dynes.}$$

364. Absolute electrometer. We are now in a position to measure in a practical manner the potential of a conductor in absolute units.

The instrument by which this is done was invented by Lord Kelvin, and is called an **Electrometer**, or, from an important feature of its design, the **Guard-ring Electrometer.**

This instrument consists essentially of an insulated flat circular conducting plate (C, Fig. 205), which can be raised or lowered by a micrometer screw H, working in a fixed nut E.

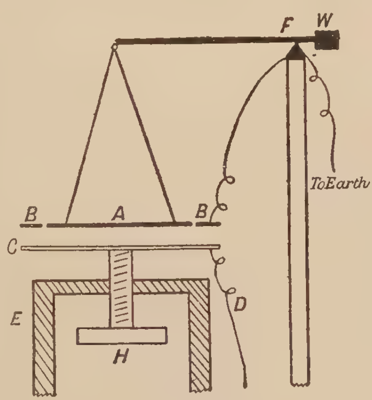


Fig. 205.

This plate can be connected by a wire D to the body whose potential V is to be determined.

Above and parallel to it is another circular metallic plate A, hung from the end of a kind of steelyard whose fulcrum is at F; this plate, when the bar of the steelyard is exactly horizontal, lies exactly in the plane of a concentric ring B (the guard-ring), which it nearly touches and with which it is in metallic connection. The function of this ring is to make A practically a part of a much larger plate, so that the irregularity of distribution of lines of force from C to A and B may not affect A.

Both A and B are connected to earth, and hence together with C

may be considered to form a condenser such as we have been considering. If we assume that C becomes charged to a surface-density ρ, by being brought up to the potential V of the body which it is required to measure, then A will have a surface-density $-\rho$, and by Article 363 the force of attraction F between A and C, if the area of A is S sq. cm., is

$$F = 2\pi\rho^2 S \text{ dynes.}$$

But by Article 361 the difference of potential is given by

$$V = 4\pi\rho d,$$

where d cm. is the distance between the plates A and C.

If we eliminate ρ between these two equations, we have

$$\frac{F}{2\pi S} = \left(\frac{V}{4\pi d}\right)^2,$$

or,

$$V = \sqrt{16\pi^2 d^2 \times \frac{F}{2\pi S}}$$

$$= \sqrt{\frac{8\pi F d^2}{S}}$$

$$= d\sqrt{\frac{8\pi F}{S}}.$$

Hence, since we can measure the force F, the distance d, and the area S, we obtain a measure in absolute units of the potential V. For this purpose a sensitive balance would be substituted for the steelyard, and A would then take the place of one of its pans.

365. In practice it is found best to work with a constant force tending to raise A above the plane of the guard-ring (produced by the weight W) and to balance this force by raising or lowering C by means of the micrometer screw, thus changing d. If we know F and S, which are 'instrumental constants,' we can then find V in any experiment by observing the distance d, which must separate the plates so that their attraction may balance the counterpoise on the steelyard. This state of things can be accurately observed by examining the position of the end of the arm of the steelyard by a fixed microscope. As the equilibrium in this position is unstable, stops must be provided to limit the motion of the steelyard on each side of this position.

Such an instrument is not well adapted to the measurement of small differences of potential, since the force varies as the *square* of the potential difference between the plates and therefore becomes very small indeed when the potential difference is small. In addition to this, the body whose potential is to be measured must be of large capacity in order that its potential may not be affected by the loss of the electricity needed to charge the plate C.

In the actual instrument there are, of course, a very large number of additions to the simple form above described, but this is sufficient to indicate the principles on which a *numerical* measurement of the potential of a body can be made.

366*. Connection between electrostatic and electro-magnetic units. The guard-ring electrometer can be used to determine a quantity of considerable importance in electrical theory, the relationship between corresponding quantities (e. g. potential difference, capacity, &c.) as defined respectively in electrostatics and voltaic electricity.

It can be applied directly in the case of potential difference, because we can produce a difference of potential of about 1,000 volts by means of a battery, and measure its E.M.F. in volts by Poggendorff's method (p. **115**); then we can connect one terminal to the movable plate of the electrometer and the other to the guard-ring and trap-door, and determine the difference of potential by the formula on p. 280.

It will be found that the latter number is almost exactly $\frac{1}{300}$ of the number of volts.

Hence the electrostatic *unit* must be equal to 300 volts, in order that the quantity expressed in such units may be $\frac{1}{300}$ of the number expressing that quantity in volts.

We know that 1 volt was defined so as to be equal to 10^8 absolute electro-magnetic units of potential difference, so we learn that the electrostatic unit of potential difference is 300×10^8, or 3×10^{10}, or thirty thousand million times the electro-magnetic unit, both being reckoned on the C.G.S. system.

The fact that this number is, within the limits of experimental error, the same as the velocity of light in vacuo measured in cm. per sec., confirms a speculation of Clerk Maxwell's, that light is an electro-magnetic phenomenon consisting of waves of electric displacement propagated through the dielectric.

367. Quadrant electrometer. If we wish to measure the difference of potential between two bodies, when that difference is small, we must employ a Quadrant Electrometer, invented by Lord Kelvin.

It consists of a flat needle of aluminium, shaped like a figure 8, supported at its centre by a thin wire so as to hang horizontally, and retained in position by the weak controlling force of torsion of the wire.

This needle hangs, as in the bird's-eye view shown in Fig. 206, above four insulated metallic quadrants A and B, opposite quadrants being connected together.

The needle is charged to a high potential, and kept at that potential by being connected to the inner coating of a charged Leyden jar. One

opposite pair of quadrants (A) is connected to one of the bodies, and the other pair to the other; if these are at a different potential the needle (C) will be repelled by one pair and attracted by the other, with a force depending both on the difference of potential of A and B, and on the difference between the average of these potentials and that of the needle *.

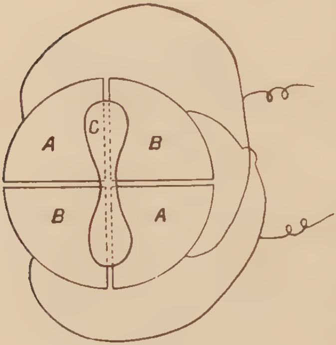


Fig. 206.

Hence the needle will be turned round through an angle against the force of torsion of the wire, and the angle of twist will give a measure of these potential differences.

To ensure accuracy the quadrants are usually not in the form of plates, but of shallow boxes consisting of quadrant-shaped plates above and below the plane of the needle, connected round their outer edges by a vertical wall of metal. The needle is then repelled out of one pair of boxes and into the other with a force given by the following formula:

$$F = A\,(V_1 - V_2)\left(V_3 - \frac{V_1 + V_2}{2}\right),$$

where A is an instrumental constant,

V_1 is the potential of the quadrants A,
V_2 „ „ „ „ B,
V_3 „ „ the needle.

If V_3 is very large compared with V_1 and V_2, this force becomes

$$F = A\,V_3\,(V_1 - V_2),$$

so that, since the restoring force of torsion of the wire is proportional to the angle through which its end is turned, *the angle turned through by the needle is proportional to the difference of potentials of the quadrants.* Such a high degree of sensitiveness can be attained with this instrument that it will accurately indicate ·02 of a volt (see p. 256).

* This statement, which is rigorously true only under certain conditions, follows from mathematical reasoning too long to be given here.

NUMERICAL EXERCISES

Magnetism

1. A pole of strength 40 is placed 20 cms. due E. of the needle of a magnetometer, H being ·176. Find the deflection of the needle.

2. A magnet-pole of strength 20 attracts another at a distance of 5 cms. with a force of 1 dyne; what is the strength of the second?

3. Two equal magnet-poles, 5 cms. apart, repel each other with a force of 3 dynes; what is the strength of each?

4. A bar-magnet is 6 cms. long and has poles of strength 50 at each end; what force will it exert at a point on its axis 27 cms. from the centre of the magnet?

5. A bar-magnet 10 cms. long is placed as in Fig. 26, with its centre 25 cms. from the centre of the magnetometer; the deflection produced is 30°. Find the magnetic moment of the magnet.

6. A bar-magnet 8 cms. long is placed as in Fig. 26, with its centre 24 cms. from the centre of the magnetometer; when another bar-magnet 16 cms. long is similarly placed with its centre at the same distance away on the opposite side of the magnetometer there is no deflection. Compare the magnetic moments of the two magnets.

7. A small compass-needle makes 30 oscillations per minute when 15 cms. distant from a magnet-pole; what number of oscillations will it make per minute when 20 cms. distant from the same pole?

8. An 'oscillating needle' made 24 oscillations per minute at Kew in 1860; what was its frequency there in 1900?

9. An oscillating needle makes 24 oscillations per minute under the earth's force alone (H = ·18); a S. pole of strength 200 is put 25 cms. due N. of the needle; how many oscillations will the needle make per minute?

10. An oscillating needle makes 20 oscillations per minute under the earth's force alone, where H = ·176; how many oscillations will it make per minute when placed at a point in the axis of a bar-magnet, 8 cms. long, whose moment is 520, at a distance of 20 cms. from its centre, the earth's force being neglected?

11. Find the vertical force, and the total force, at a place where the dip is 67° and H is ·18.

Voltaic Electricity

12. A certain current deposits 1 grm. of silver in an hour; how long will it take to deposit 1 grm. of copper?

13. What current is needed to deposit 1 grm. of copper in 32 mins.?

14. A current deposits ·193 grm. of copper in 54 mins. 10 secs.; what is its magnitude in ampères?

15. The coil of a tangent galvanometer consists of 2 turns of radius 10 cms. What current in the coil will produce a deflection of 45°, where $H = \cdot 18$?

16. Find the reduction factor of a tangent galvanometer having 50 turns of wire, the diameter of the coil being 40 cms., and H being ·176.

17. A certain current produces a deflection of 30° in a tangent galvanometer at a place where $H = \cdot 17$; what deflection will it produce at a place where $H = \cdot 18$?

18. A Daniell cell (1·07 volts) gives a deflection of 25° in a high-resistance tangent galvanometer; another cell produces a deflection of 42°; what is its E.M.F.?

19. A cell whose E.M.F. is 1·1 volts and internal resistance is 2 ohms is connected to a wire having a resistance of 50 ohms; what current will flow?

20. What is the internal resistance of a cell of E.M.F. 1·5 volts which produces a current of 1 ampère through an external resistance of 1·1 ohms?

21. An incandescent lamp takes a current of ·32 amp. when an E.M.F. of 100 volts is maintained between its terminals; what is its resistance?

22. An incandescent lamp takes a current of ·6 amp. when an E.M.F. of 100 volts is maintained between its terminals; what current will flow if the E.M.F. is raised to 103 volts?

23. A glow-lamp has a resistance, when hot, of 4 ohms, and can be worked by 6 chromic acid cells in series, each of E.M.F. 2 volts and internal resistance ·166 ohm; what current is needed to light the lamp?

24. Find how many cells, each of E.M.F. 1·1 volts and resistance 3 ohms, must be connected in series to produce a current of ·125 amp. through a resistance of 58 ohms.

25. A conductor, whose resistance is known to be ·012 ohm, forms part of a circuit in which current is flowing; the E.M.F. between the ends of the conductor is found to be 13·2 volts; what is the current?

26. The E.M.F. of a cell on open circuit is 1·4 volts; when connected to a coil of resistance 6 ohms the E.M.F. between its terminals is found to fall to ·9 volt. Find the current supplied by the cell, and the resistance of the cell.

27. The E.M.F. of two similar cells in series on open circuit is found to be 2·2 volts; when connected in series with an ampèremeter, whose resistance is 1·2 ohms, and a resistance-coil of 15 ohms, the current supplied is found to be ·08 amp. Find the internal resistance of the battery.

28. A battery consists of 5 Leclanché cells in series, each having an E.M.F. of 1·45 volts and a resistance of ·4 ohm; what current will it drive through an external resistance of 2 ohms?

29. If the cells in Exercise 28 are all connected in parallel, what current will be produced through the 2 ohms?

30. What is the least number of cells, each of 1·5 volts and ·8 ohm internal resistance, that will drive a current of ·5 amp. through an external resistance of 100 ohms?

31. A Daniell cell of unknown E.M.F. is connected in opposition to a Leclanché (E.M.F. 1·45 volts), and the battery gives a current of ·05 amp. through a galvanometer. When the Daniell cell is reversed and connected in series with the Leclanché, the current is found to be ·4 amp. What is the E.M.F. of the Daniell cell? Find also the resistance of the circuit.

32. A battery of E.M.F. 7·25 volts is connected to a resistance of 6 ohms, and the current produced is ·9 amp. (1) What is the internal resistance of the battery? (2) How much resistance must be added to the external circuit in order that the current may be halved?

33. The greatest allowable current for charging an accumulator (whose resistance is negligible) is ·5 amp. What resistance must be put in series with it in order that it may safely be attached to electric-light mains of which the E.M.F. is 100 volts?

34. The back E.M.F. of an arc-lamp is 40 volts; what resistance must be put in series with it for use across mains at 110 volts in order to secure a current of 10 amps.?

35. The back E.M.F. of an accumulator while being charged is 2·25; neglecting the internal resistance, what current will be forced through 2 accumulators in series by a battery of 3 chromic acid cells, each of E.M.F. 1·8 volts and resistance ·4 ohm?

36. A galvanometer of resistance 4 ohms is shunted by a wire of resistance 1 ohm; what fraction of the total current will pass through the galvanometer?

37. A galvanometer has a resistance of 100 ohms, and it is desired to make it $\frac{1}{10}$ as sensitive by a shunt consisting of platinoid wire. The wire is found to have a resistance of ·023 ohm per cm. What length of wire will be needed?

38. The shunt-coils of the field-magnets of a dynamo have a resistance of 400 ohms, and are connected to the brushes, where a constant E.M.F. of 456 volts is maintained; what current flows through the shunt-coils?

39. Find the resistance of the shunt which will take $\frac{99}{100}$ of the total current, when the instrument for which it is designed has a resistance of 325 ohms.

40. A voltmeter has a resistance of 160 ohms, and correctly registers the E.M.F. of an accumulator; what E.M.F. will it mark when coupled to a cell of (true) E.M.F. 2 volts and resistance 50 ohms?

41. The resistance of a 16-c.p. glow-lamp is 600 ohms, and of an 8-c.p. glow-lamp is 1,200 ohms; what will be the resistance of the two coupled in parallel?

42. The internal resistances of three Daniell cells are 3, 4, and 5 ohms respectively; what will be the resistance of the battery formed by putting the three in parallel?

43. Two coils of resistances 31 and 94 ohms are put in parallel; a battery

of E.M.F. 3 volts and internal resistance 1 ohm is connected to them; what current will flow through each coil?

44. Two exactly similar wires of copper and iron are connected in parallel; how will a current divide itself between them?

45. Find the resistance of a copper wire 50 cms. long and ·6 cm. diameter.

46. Find the resistance of a manganin wire 600 cms. long, No. 18 gauge.

47. Find the resistance of a rectangular copper strap, 1 kilometre long, 2 cms. broad, ·2 cm. thick.

48. What length of No. 24 iron wire will have a resistance of 5 ohms?

49. What length of copper wire will have the same resistance as 43 cms. of iron wire of the same gauge?

50. Find the gauge of copper wire that will have the same resistance per mile as No. 10 iron wire.

51. The resistance of a new 1-ohm coil is found to be 1·008 ohms; what length of platinoid wire, of which 81 cms. give a resistance of 1 ohm, must be put in parallel with it to produce an accurate 1-ohm coil?

52. A tangent galvanometer has 1 turn of wire of radius 7 cms.; find the reduction factor for ampères, if $H = \cdot 17$.

53. A tangent galvanometer has 30 turns of wire each of radius 18 cms., and the value of H is ·18; find the number of ampères flowing when the deflection is 32°.

54. A tangent galvanometer has a resistance of 1 ohm; a cell of E.M.F. 1·1 volts and resistance ·3 ohm produces a deflection in it of 75°. Find the reduction factor.

55. Compare the magnitudes of two currents that produce deflections of 18° and 65° in the same tangent galvanometer.

56. The coil of a tangent galvanometer has a radius of 11 cms., and in a magnetic field of strength ·176 a current of ·007 amp. produces a deflection of 38°. Find the number of turns in the coil.

57. A copper voltameter and tangent galvanometer are put in series, and a constant current is run through them for 18 minutes 37 secs. ·87 grm. of copper is deposited and the deflection of the galvanometer is 14°. Find the reduction factor.

58. A tangent galvanometer is employed as a sine galvanometer, and a certain current gives a deflection of 54°; what deflection would the same current produce in the same instrument if used as a tangent galvanometer?

59. The resistance of a coil of copper wire at 0° C. is 1 ohm; what will be its resistance at 100° C.?

60. Assuming that the resistance of a pure metal, such as copper, decreases uniformly with the temperature, find the temperature at which it becomes a perfect conductor.

61. A piece of platinum wire has a resistance at 0°C. of 1 ohm; what is its resistance (1) at the melting-point of gold (1045° C.), (2) at the boiling-point of carbon dioxide (−78° C.)?

62. Plot the curve showing magnetism (B) produced in a piece of steel for

variations in the magnetizing force (H) when carried through a complete cycle, as in Experiment 75, from the following data:—

H	B	H	B	H	B	H	B
10	1600	70	14000	−50	−11700	−30	−12500
20	5600	60	13700	−60	−12500	−20	−12000
30	8500	50	13500	−70	−13100	−10	−11300
40	10500	40	13100	−80	−14000	0	−10200
50	11700	30	12500	−90	−14100	10	−8000
60	12400	20	12000	−100	−14100	20	−2000
70	13400	10	11300	−90	−14100	30	6000
80	13700	0	10200	−80	−14000	40	10000
90	14100	−10	8000	−70	−14000	50	11700
100	14100	−20	2000	−60	−13700	60	12500
90	14100	−30	−6000	−50	−13500	70	13100
80	14000	−40	−10000	−40	−13100	80	13700

63. If 1 c.c. of hydrogen weighs ·0000896 grm., find the volume of hydrogen liberated by the current which deposits 1 grm. of silver.

64. If 1 c.c. of hydrogen weighs ·0000896 grm., find the total volume of gases liberated in the electrolysis of water by 3 ampères in an hour.

65. Assuming that the solution of zinc in a cell takes place at the same rate as its deposition by the current during the electrolysis of zinc sulphate, calculate the amount of zinc used up in a Daniell cell which furnishes ·3 amp. for 5 hours.

66. A current of 3 ampères flows for 10 minutes through a wire whose resistance is 10 ohms; how much heat is produced?

67. Find the rate of production of heat in therms per second, when 10 ampères flow through a coil of 21 ohms.

68. Compare the amounts of heat liberated by the same current while flowing in series through exactly similar wires of copper and platinum.

69. A battery is joined up to two exactly similar wires of copper and iron arranged in parallel; compare the amounts of heat produced in the two wires.

70. A glow-lamp takes ·6 amp. at 220 volts; how many watts does it consume?

71. A glow-lamp requires 3 watts per candle-power; how many ampères are used by a 32-c.p. lamp made for an E.M.F. of 100 volts?

72. Assuming no waste of energy, how many glow-lamps of 16 c.p., each using 4 watts per c.p., could be kept alight by an engine of 1 horse-power? (1 horse-power = 746 watts.)

73. If an arc-lamp needs $\frac{3}{4}$ watt per candle-power, and its back E.M.F. is 40 volts, what number of ampères are needed to produce 1,000 c.p.?

74. An incandescent lamp of 16 c.p. takes a current of ·75 amp. with an E.M.F. of 60 volts between its terminals; find the amount of heat generated in an hour, and the time it would take to raise 1 pint ($1\frac{1}{4}$ lb. or 568 grms.) of water from 15° C. to 100° C.

75. An engine of 150 horse-power drives a dynamo which delivers 220 ampères and maintains an E.M.F. of 450 volts between its brushes. Compare the amount of energy supplied with that received by the dynamo. (1 horse-power = 746 watts.)

APPENDIX A

Resistance derived from P.D. and Current

Many students find difficulty in distinguishing clearly between current and E.M.F., probably because the same kind of instrument is commonly used for measuring these quantities. Now that electrostatic voltmeters have become ordinary commercial instruments, and many laboratories are supplied with D.C. mains, it is easy to revert to the traditional sequence and to treat P.D. and current as fundamental, and resistance as derived from them. Ohm's Law can then be obtained in its original form.

There are two disadvantages in doing so; first, resistance is a physical property of a conductor which a student can easily realize, and it seems to him artificial to treat it as derived from the less obvious quantity P.D.; second, the electrostatic voltmeter is better adapted for use on a lecture table than in a beginner's laboratory. But the early attainment of a clear conception of P.D. may well be held to outweigh the former objection; and as to the second, as soon as Ohm's Law has been established in the lecture-room, and the use of the moving coil voltmeter has been justified, the laboratory course can be resumed on the ordinary lines. Hence it may be convenient to give here an outline of the procedure which experience has shown to be profitable.

In view of the widespread use of electricity and the interest which the majority of young boys take in it, it has been found advantageous to preface the methodical quantitative treatment of the subject by a descriptive course of the phenomena of D.C. electricity, solely qualitative and treated as demonstration lectures. This deals with the general idea of a current, produced by cells and tested by glow lamps, compass needles, and electric bells; the idea of resistance and the method of putting cells in series to overcome it; the needle telegraph, electromagnet, electric bell, Morse telegraph; moving coil galvanometers and simple electromotors; simple dynamos; electroplating.

The methodical course begins with measurement of current, as in Chaps. VI and VII. The idea of P.D. is then introduced by analogy of steam or water pressure in a steam engine or turbine, whether

actually driving the machine or only ready to do so. The existence of the P.D. between the electric supply mains can be shown by the attraction of a gold leaf, connected (through a very high resistance, for safety) to one of the terminals, towards a fixed metal plate connected to the other. In order to measure the force of attraction we must employ an electrostatic voltmeter; we do not need to know the law connecting the force and the deflection, but only that a greater force produces a greater deflection. If we increase the number of cells in a battery connected to the terminals of the voltmeter, or add a battery of cells to the supply mains, we find that the deflection is increased. It is open to us to fix the numerical meaning of P.D. in any way we please; we now do so by saying that *a battery of N similar cells in series gives N times the P.D. of a single cell.*

Further, we define the *unit P.D.* (which we call a Volt) by means of a particular cell, the Weston Normal Cell. It would appear most convenient to define a volt as the P.D. given by this cell; but the value of a volt is fixed by theoretical reasoning based on 'absolute units,' and this gives for a Weston cell at 20° C. a P.D. of 1·0184 volts. Hence we can graduate the scale of the voltmeter by using different numbers of Weston cells in series, and filling up the gaps by interpolation; or we can check the graduations if already made.

Ohm's Law can now be established by taking a battery of cells driving current through a number of coils PQ, QR, RS, &c., and an ammeter A. Connect an electrostatic voltmeter (V) to Q and R. Vary the current in the circuit, and note corresponding readings of A and V. It will be found that *the current through a given conductor is directly proportional to the P.D. between its ends.* The simplicity of this connexion justifies our choice of the definition of P.D.

The numerical value of a resistance now follows. In the above arrangement keep the current constant and test the P.D. between Q and R, and between R and S, &c. We find that the P.D. needed to drive a certain current through the wire QR is not the same as that needed to drive the same current through RS. We often want to know what P.D. will be needed to drive any given current through a certain wire; if we know the P.D. required to drive 1 amp. through it we can calculate (by Ohm's Law) the P.D. required for any other current. The P.D. in volts needed for 1 amp. is called the *Resistance* of the wire, measured in Ohms; more generally, *the resistance of a conductor is the ratio of the P.D. between its ends to the current flowing through it.* Measurement of resistance in ohms follows as in

Art. 113. Ohm's Law can now be given in its modern commercial form.

The electrostatic voltmeter is delicate and not well adapted to measuring low voltages; the voltmeter ordinarily used works on a different principle, depending on Ohm's Law. It consists of a sensitive ammeter in series with a wire of high resistance. Suppose the total resistance of the combination, as measured by the above method, is R ohms; if the terminals are connected to two points between which a P.D. of V volts is maintained, a current of V/R amps. will flow through the instrument. As R is constant for a given instrument, this current is directly proportional to V, and the instrument can be provided with a scale to read volts direct. The sole disadvantage of this form of voltmeter is that it takes a little current and so disturbs the circuit to which it is connected; but in most cases the current is so small that the disturbance is negligible in practice.

The idea of E.M.F. can now be introduced, and a cell described as a seat of E.M.F. and a resistance; hence Ohm's Law for a complete circuit.

APPENDIX B

THE following data refer to wires as supplied by the London Electric Wire Co., of Playhouse Yard, Golden Lane, E.C.

TABLE OF SIZES, WEIGHTS, AND RESISTANCES OF COPPER WIRES.

Size.			Weight.		Resistance at 60° F.		
S.W.G.	Inch.	m/m.	1,000 Yds.	Mile.	1,000 Yds.	Per Mile.	Per lb.
			lb.	lb.	ohms.	ohms.	
8	·160	4·064	232·47	409·16	1·178	2·07	·0051
9	·144	3·658	188·30	331·42	1·455	2·56	·0077
10	·128	3·251	148·78	261·86	1·842	3·24	·0124
11	·116	2·946	122·19	215·06	2·242	3·94	·0183
12	·104	2·642	98·22	172·87	2·788	4·89	·0284
13	·092	2·336	76·86	135·28	3·564	6·28	·0464
14	·080	2·032	58·12	102·29	4·714	8·29	·0811
15	·072	1·829	47·08	82·85	5·819	10·23	·1237
16	·064	1·626	37·19	65·47	7·367	12·97	·1981
17	·056	1·422	28·48	50·12	9·620	16·91	·3379
18	·048	1·219	20·92	36·82	13·097	23·06	·6261
19	·040	1·016	14·53	25·57	18·857	33·19	1·298
20	·036	·914	11·77	20·71	23·280	40·94	1·979
21	·032	·813	9·29	16·37	29·490	51·83	3·169
22	·028	·711	7·12	12·53	38·480	67·69	5·407
23	·024	·610	5·23	9·21	52·390	93·55	10·017
24	·022	·559	4·39	7·74	62·410	111·3	14·188
25	·020	·508	3·63	6·40	75·480	134·7	20·772
26	·018	·457	2·94	5·18	93·200	166·3	31·659
27	·0164	·417	2·44	4·30	112·300	200·4	45·943
28	·0148	·376	1·99	3·50	137·700	246·0	69·270
30	·0124	·315	1·40	2·46	196·800	350·3	140·570
32	·0108	·274	1·06	1·86	258·700	462·0	244·290
34	·0092	·2337	·77	1·35	356·500	636·6	463·910
36	·0076	·1930	·52	·923	522·400	933·0	996·180
38	·0060	·1524	·33	·575	838·200	1497	2564
40	·0048	·1219	·21	·368	1315	2338	6261
42	·0040	·1016	·145	·256	1886	3367	12982
44	·0032	·0813	·093	·164	2947	5262	31694
46	·0024	·0610	·052	·092	5239	9355	100171
47	·0020	·0508	·036	·064	7548	13470	207720

PLATINOID WIRE.

Resistance (approximate).		
S.W.G.	Per lb. Ohms.	Per 1,000 yds. Ohms.
8	·1241	28·852
10	·3031	45·084
12	·6957	68·292
14	1·9869	115·416
16	4·8520	180·338
18	15·3312	320·601
19	31·7952	461·664
20	48·4602	569·952
21	77·6480	721·368
22	132·4272	942·192
23	245·3280	1282·392
24	347·4720	1526·184
25	508·7280	1846·656
26	775·3680	2279·808
27	1125·2160	2746·440
28	1696·4880	3372·264
30	3442·8000	4803·984
32	5982·7200	6332·904
34	11362	8727·120
36	24398	12789·640
38	62805	20518·560
40	153333	32060·160
42	317904	46166
44	784280	72136
46	2453280	128239
47	5087280	184665

CARRYING CAPACITY OF PLATINOID.

It has been found that platinoid wires, when exposed to the atmosphere, attain the temperature of blood-heat, as follows :—

No. 20 with 1·8 amps.
,, 18 ,, 3·3 ,,
,, 16 ,, 6·0 ,,
,, 14 ,, 10·0 ,,

No. 12 with 15 amps.
,, 10 ,, 25 ,,
,, 8 ,, 37 ,,

APPENDIX C

Angles and their Tangents

A right angle is divided into ninety equal parts, called degrees. Each of these is usually subdivided into sixty equal parts called minutes, and so on; but for practical purposes, the position of a pointer moving over a scale marked in degrees will only be estimated with any approach to accuracy to *tenths* of a degree, an estimation to which the student is accustomed. The **tangent** of an angle (such as APM, Fig. 208) is a number, which is obtained from the angle itself by a geometrical construction, *or* deduced by a mathematical calculation. The value of this number has been calculated for a very large number of angles, and these values are given in the books of tables in common use.

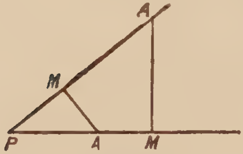


Fig. 208.

The geometrical construction which gives us the definition of the tangent of an angle is as follows:—From any point A on either of the lines forming the angle APM draw a perpendicular AM on the other line. Then the fraction

$$\frac{AM}{MP}$$

is called the tangent of APM, or **tan APM.**

It can be proved by geometry, or verified by actual measurement, that the value of this fraction does not depend on the position chosen for A, nor on whether it is taken on PA or PM.

The *sine* of APM is defined to be the value of the ratio

$$\frac{AM}{AP}.$$

APPENDIX D

To Construct a Resistance-Coil

Cut a piece of cardboard as in Fig. 209 on which to wind the wire, or use a cotton-reel or other piece of wood.

Next cut two tags of *thin* sheet copper, of the shape of *A A*, and of such a size as to go conveniently under a binding screw.

Solder the wire to the tags, so that the correct length is free between the tags. To do this, clean the ends of the wire and the tag with emery-cloth; moisten both surfaces to be soldered together with zinc chloride solution; put a bit of soft solder on the tag at the place to be soldered and hold the point of a hot soldering-bit against it until the solder just runs on to the copper as mercury runs on zinc when you amalgamate it. The 'soldering-bit' should be clean, and not red hot, but hot enough to melt solder *readily*.

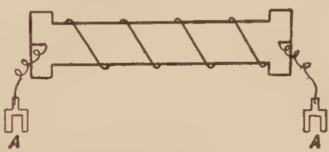


Fig. 209.

Do the same with the end of the wire to be soldered (this operation is called 'tinning' and should always precede any attempt to solder together two pieces of metal); then hold together the wire and tag at the points to be united, adding a bit of solder if necessary, and hold the hot soldering-bit against them until the solder on them unites.

After this it is well to wash the joint with water to clear away any zinc chloride that is left, or the joint may corrode. The use of resin instead of zinc chloride obviates the necessity of washing, but the process is not so easy.

Of course, instead of using the 'bit,' all the above operations can be performed with a Bunsen flame.

Now wind the wire on the cardboard, passing the ends through slits to hold them; write on the cardboard the resistance of the coil, the exact gauge and length of the wire.

APPENDIX E

Determination of the Values of H and M

It was stated on p. 30 that the time of swing of a suspended magnet depends not only on its magnetic moment, but also on the mass and the distribution of that mass about the axis of suspension. There is an expression called the Moment of Inertia of a body, which involves these two factors. Its value, usually denoted by I, can be calculated for most bodies by means of the Integral Calculus, and there is a simple formula by which it may be computed for a rectangular bar movable round an axis passing through its centre at right angles to one of its faces *.

The actual formula, established in books on Dynamics, connecting together the time (T secs.) of one to-and-fro oscillation, the strength of the magnetic field in which the magnet hangs (H dynes on one unit pole), the moment of inertia of the magnet (I) and the Magnetic Moment of the magnet (M), is

$$T = 2\pi\sqrt{\frac{I}{MH}};$$

hence

$$MH = \frac{4\pi^2 I}{T^2} \quad \ldots\ldots\ldots\ldots \quad \text{(B)}$$

From the formula A on p. 29 we have

$$\frac{M}{H} = \frac{(d^2 - l^2)^2}{2d}\tan\theta. \quad \ldots\ldots\ldots \quad \text{(A)}$$

From these two equations we can eliminate either M or H, and so obtain the value of the other in terms of a number of quantities all of which can be measured.

The process of finding the value of M or H is therefore as follows:— The value of $\frac{M}{H}$ is determined exactly as in Experiment 21, using a rectangular bar-magnet about 10 cm. long. This magnet is then

* In this case $I = W \times \frac{a^2 + b^2}{12}$, where W is the mass of the bar in grammes, a and b the length and breadth of the bar in cm. (looking at it along the axis about which it turns).

suspended at the place previously occupied by the magnetometer, and the time of one complete oscillation determined as in Experiment 23. The weight of the bar-magnet is determined, and its moment of inertia calculated. Then its magnetic moment can be deduced directly from the formula

$$M = \frac{\pi\,(d^2 - l^2)}{T}\sqrt{\frac{2\,I\tan\theta}{d}},$$

and H from the formula

$$H = \frac{2\,\pi}{T\,(d^2 - l^2)}\sqrt{\frac{2\,I\,d}{\tan\theta}},$$

where d, l, θ, I, and T have the meanings previously explained.

APPENDIX F

THE FLUXMETER

GRASSOT'S Fluxmeter is an instrument which records, by the movement of a pointer over a scale, the total number of lines of magnetic force which cross a wire connecting its terminals. This wire may be coiled into a ring, and then the pointer records any increase or decrease in the number of lines of force linked with the ring; for example, if the pointer stands at zero and the ring is slipped half-way down a bar-magnet, the pointer moves to a scale division corresponding to the number of lines emanating from the pole of the magnet, and remains there until the ring is slipped off the magnet again, when it returns to zero.

The instrument is very convenient for making many of the experiments described in this book and elsewhere ; for example, the magnetic condition of bar-magnets can be ascertained without any trouble, the field in the neighbourhood of large magnets or the air gap of a dynamo can be explored, the total number of lines through a solenoid can be counted and the effect of an iron core shown numerically, and the magnetization curve for a given sample of iron obtained very easily. It is compact, portable, and comparatively robust, and only requires levelling for use.

APPENDIX G

Alternative Course of Electrostatics

Part III is arranged to be independent of any previous knowledge of Voltaic Electricity. If it be desired to give students who have read Parts I and II a short course of statical electricity, of a utilitarian rather than an educational nature, the following outline may be convenient. The general idea is to eliminate unnecessary difficulties, both for the learner in comprehension and for the lecturer in manipulation; and by omitting non-essentials to give greater clearness to the ideas which are needed in current electricity. The procedure is analogous to the study of Heat, where the beginner's sole instrument is a thermometer, and no attempt is made to explain how a flame produces heat, nor why the capacity of a pound of brass and water differ.

I. Single cell and quadrant electrometer or battery and electrostatic voltmeter. Explain the principle of action of the instrument in outline. Show the *new* property of electricity, the mechanical force of attraction between two bodies connected to the poles of a battery. These bodies said to be charged with '$+^{\text{ve}}$ and $-^{\text{ve}}$ electricity'. If conductor interposed, these charges neutralize each other, making an electric current in the conductor; show a condenser charged to 2 volts, or a Leyden Jar to P.D. of mains, discharged through a galvanometer (condenser described, without explanation, which would involve induction). The battery continually renews the charges (shown by interposing a high resistance across terminals of voltmeter).

If one pole of battery is earthed, a body connected to other pole attracts an earthed body.

II. Potential specified as depending on this attraction (i.e. the tendency of electricity to get to earth). If potential is high, attraction is greater (and less delicate instrument required). Volts analogous to degrees of temperature, voltmeters to thermometers; define zero of potential, but not magnitude of a volt. Potential either + or −, as with temperature, but voltmeter deflects same way for both.

III. Show (without describing it or explaining its principle of action) a **Voss or Wimshurst** machine; earth one prime conductor, show that the other attracts a light suspended earthed body (rough voltmeter).

Carry off charges on an insulated ball, give them to a condenser or Leyden Jar connected to a voltmeter (second terminals of each earthed). Each charge raises potential, just as a succession of red-hot shot dropped into water raises its temperature.

Charge a jar connected to a voltmeter, by carrier ball or wire from machine or electric lighting mains; disconnect machine, and connect in parallel with uncharged jar; show drop of potential. Hence **qualitative** idea of Capacity (analogy with mixing hot and cold water, and capacity for heat), and Quantity of Electricity as depending on capacity and potential (cf. method of defining quantity of heat).

IV. Potential the same at all points of a conductor, shown by wire from voltmeter to knob and inner coat of jar. Analogy with temperature in steady state.

V. Induction (heat analogy no longer applicable). Potential of insulated plate raised by neighbourhood of another plate at high potential.

(Stand jar on insulator; connect its outer coat to voltmeter; charge inner; potential of outer rises but returns to zero when inner discharged.)

Increase of capacity of plate caused by neighbourhood of earthed plate.

(Jar on insulator, inner coat to voltmeter; charge inner coat; earth outer coat and potential of inner falls, and jar must be further charged to restore potential.)

Hence capacity depends on thickness of **dielectric**.

Ordinary form of sheet condenser, and Leyden Jar as used in wireless telegraphy.

Specific inductive capacity of dielectric.

(Mix two condensers, one charged and having air as dielectric, the other uncharged, having paraffin as dielectric, otherwise similar; observe final potential.)

Seat of charge in Leyden Jar (by dissected jar).

VI. Miscellaneous experiments (as required).

Discharge by points; lightning conductors and arresters.

Discharge through gases; sparking distance dependent on pressure of gas and P.D.

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